STUDY OF EFFECTS OF INTERPLANETARY PHENOMENA ON COSMIC RAY VARIATIONS

ABSTRACT

THESIS SUBMITTED FOR THE AWARD OF
THE DEGREE OF
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BY

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ABSTRACT

Galactice cosmic ray particles which enter the heliosphere are affected by the large-scale interplanetary magnetic field (IMF) and its small-scale irregularities during their passage to the Earth. These particles are scattered by magnetic irregularities whose scale-sizes are comparable to their Larmour randius, and their motions are like a random walk. As a result of this the observed anisotropy of cosmic rays is very small. Intensity and anisotropy of cosmic rays are modulated by the condition of interplanetary medium. Conversely, the understanding of the modulation process can be used for diagonising the interplanetary condition through the observation of cosmic rays.

In this thesis we have studied the effects of interplanetary phenomena on cosmic ray variations. Specifically, we have studied the cosmic ray intensity variation near the current sheet, the effect of magnetic clouds and interplanetary shocks on cosmic ray intensity variations. The diurnal anisotropies during the passage of these magnetic clouds and interplanetary shocks on the Earth, have also been studied in detail.

This thesis has been divided into five Chapters.

In Chapter I, the general introduction of motivating this work presented in the thesis, has been given. Both theoretical and observational point of views of taking up this study with the support of relevent cited literature, have been discussed in this Chapter.

Chapter II deals with a new technique developed by us to separate the world-wide component and diurnal variation from the time records of cosmic ray intensity variation at any neutron monitoring station. Since a long time ago the need of the separation of these two components from the time records of cosmic ray intensity variation had been felt. Without separating the world-wide component from the time records of cosmic ray intensity variation, it was not possible to find out diurnal amplitude and phase during the passage of specific type of perturbations such as magnetic clouds and interplanetary shocks. The development of this technique has paved the way of calculating diurnal amplitude and phase during the passage of specific type of perturbations on the Earth. These specific type of perturbations produce Forbush type decreases which are non-periodic and cannot be analysed by simple harmonic analysis technique.

In Chapter III, we have studied the cosmic ray intensity variation near the interplanetary current sheet which separates the two solar hemispheres of opposite magnetic polarity. The cosmic ray neutron monitor data from the four stations located from the pole to equator, on the surface of Earth, covering almost the whole range of cut-off rigidities on the Earth, for the complete solar cycle 20 have been utilized. This period also includes a period of reversal of solar polarity. It is assumed that the current sheet is heliomagnetic equator. We have discussed the density gradients with respect to the current sheet during different solar activity periods and magnetic field conditions. With the help of these results of cosmic ray variations near the interplanetary current sheet, the possibilities of its displacement during different epochs of solar cycle have been discussed. A plausible explanation has been given for the observed results. Recently, zero latitudinal gradient within 15^{0} latitude with respect to heliographic equator has been reported on the basis of space-craft observations. Our results provide support to the above expressed recent view that probably it is the heliospheric current sheet rather than the helioequatorial plane which is of physical significance when one is calculating the latitudinal gradient of galatic cosmic rays. These results have been discussed in the light of existing theoretical and observational evidences.

In Chapter IV, the effect of three category of magnetic clouds (shock associated, interaction region associated and cold magnetic enhancement associated) on cosmic ray variation have been discussed. Forbush type decreases are observed with shock associated clouds. The effect of these specific type of perturbations on diurnal anisotropy of cosmic rays is studied in detail. The effect of the direction of magnetic field on diurnal anisotropy is also studied. The formation of density gradient perpendicular to ecliptic plane is discussed.

The role played in solar modulation of cosmic rays by drifts due to gradients and curvatures in the interplanetary magnetic field is a problem of basic importance. A significant role of drifts in modulation will result in a three dimensional cosmic ray distribution in the heliosphere very different from that inferred from models in which drifts are negligible. On the basis of our results it has been shown that one cannot neglect the terms containing perpendicular density gradient and depending upon the sense of magnetic field in the general euqation of anisotropy vector. The streaming due to $\vec{B} \times \vec{\nabla} U$ (where $\vec{B}$ is the magnetic field and $\vec{\nabla} U$ is the density gradient perpendicular to the ecliptic plane), which is superimposed on corotation streaming and gives larger diurnal amplitude for southward (+) magnetic field and less diurnal amplitude for northward (-) magnetic field, is discussed. The relation of diurnal amplitude and phase during the passage of these magnetic clouds with A_p index is shown. The results of this analysis show that diurnal amplitude and phase recovers after the departure of the magnetic clouds from the Earth. All these results have been discussed in the light of available theoretical and observational evidences.

In Chapter V, the effects of interplanetary He- shocks and non He- shocks, identified through IMP 6,7 & 8 from 1971 to 1978, have been studied on cosmic ray intensity variations and diurnal anisotropy. He- shocks have produced strongest effect on cosmic ray intensity variation and diurnal amplitude. The effect of the polarity of IMF and magnetic field of the driver gas (ejecta) is studied separately. The results are discussed in the light of Chapter IV in which the perturbations are specific and have the definite direction of the magnetic field in their front boundary. The prediction of the direction of the magnetic field in the front boundary of the driver gas (ejecta) which is coming behind the He- shocks, is made on the basis of the results obtained here and in Chapter IV in which the ejecta (magnetic clouds) have a definite direction of the magnetic field. A model which can explain the diurnal anisotropy is in progress in our group.

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Certified that the work presented in this thesis is the original work of Mr. Nathu Ram Yadav, done under my supervision.

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LIST OF PUBLICATIONS

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CONTENTS

CHAPTER I

I N T R O D U C T I O N

It is generally accepted that the galactic cosmic radiation is largely isotropic. The Sun and the interplanetary medium, however, exert a profound influence on the cosmic radiation upto helio-centric distances of 10-50 AU causing them to undergo deviation (or modulation) from isotropy and change of energy spectrum and intensity. Just as seismic waves have been used to study the interior structure of the Earth and whistlers to study the ionized portion of the Earth's outer atmosphere, intensive study of cosmic ray variation have been used as an effective probe for investigating the interplanetary conditions.

Studies of the cosmic ray modulation have played a significant role in our understanding of the nature of the interplanetary medium. The cosmic ray modulation process itself is a complicated phenomenon. Many theories developed to understand these phenomena are necessarily complicated, often inconsistent with each other and, in general, unable to make more than very general predictions. Whenever cosmic ray modulation is discussed, there is confusion because of the mixture at low energies of the galactic cosmic rays and solar accelerated particles. During solar flares, the Sun generally produces a large number of particles, normally with energies $\leq$ 100 MeV, but sometimes extending even to energies $\geq$ 1 GeV, producing a detectable enhancement in the counting rate registered by the ground based detectors (Pomerantz and Potnis, 1960; Pomerantz et. al, 1960). The acceleration of the energetic particles of approximately the same charge composition as the galactic flux occurs frequently on the Sun and contributes to the measured intensity outside the magnetic field of the Earth. In this discussion we will define the cosmic ray modulation as the temporal changes in the intensity of that component of the cosmic radiation orginating outside the solar system. Hence we will be concerned only with the galactic cosmic radiation.

The solar controlled modulation of the galactic cosmic radiations include both essentially isotropic time variations such as 11-year solar cycle variation, Forbush decreases and 27-day variations of intensity and anisotropic (spatial) variations such as the solar diurnal and semi-diurnal variations. The isotropic variations are clearly related to the effects of the changing interplanetary conditions upon the galactic cosmic radiation. The cosmic ray flux is modulated by 11-year solar cycle of sunspot activity, reaching a maximum during the quiet period of the solar cycle and a minimum near the peak of solar activity; thus establishing an inverse relationship between the solar activity and the galactic cosmic ray intensity (Forbush, 1954; Pomerantz et.al. 1958 a,b).

The original measurements of an integral cosmic ray intensity at the Earth made with ion chambers and neutron monitors focussed necessarily on temporal variations. The first observation of a Forbush decrease was made by Forbush in 1937.

With the advent of the satellite-borne instrumentation and energy spectral measurements, the focus of the 1960's and early 1970's shifted toward understanding the fundamental processes governing the solar modulation of galactic cosmic rays and inferring the unmodulated interstellar spectrum. To this end, transients were often considered an unfortunate nuisance; Forbush decreases and the 27-day wave were often suppressed by suitable averaging. Although the essential features of cosmic ray transport in interplanetary space were known in the 1950's (Convection, difussion, drifts and adiabatic deceleration) their unification in a fundamental transport equation (appropriate for the nearly isotropic particle distributions observed) by Parker in 1965 paved the way toward understanding steady state solar modulation (Gleeson and Axford, 1967; Jokipii, 1971; Fisk, 1971, 1976, 1979; Fisk et.al. 1973; Jokipii et.al. 1977; Volk et.al. 1974; Morfill et.al. 1976; Volk, 1975).

With extensive satellite coverage within the inner heliosphere and Pioneer and voyager at large heliocentric distances, however, the focuss of studies in cosmic ray transport, since the late 1970's has shifted back to temporally and spatially transient phenomena. Improved understanding of the global magnetic field and stream structure of the solar wind as well as of transient structures has encouragged studies of the associated cosmic ray transients (Burlaga, 1983; Duggal et.al.1981, 1983; Barouch and Burlaga, 1975; Burlaga et.al. 1984). It has also become clear that cosmic ray transients often dominate and obscure the underlying steady state configuration.

Unfortunately, the global structure of the heliospheric magnetic field and current sheet, solar activity and cosmic ray intensity are all temporally correlated and it is difficult to extract causal relationships from positive correlations.

The transport of galactic cosmic rays in the interplanetary magnetic field is the consequence of four basic effects:

(i) diffusion through the magentic irregularities

(ii) convection with the solar wind

(iii) cooling due to the expansion of the wind and

(iv) gradients and curvature drifts in the ambient large-scale magnetic field.

The transport equation for cosmic rays has received considerable attention over the last 20 years (Parker, 1965; Gleeson and Axford, 1967, 1968; Jokipii and Parker, 1970) with terms being emphasized in order to account for various physical phenomena. Three physical effects which have traditionally been emphasized are the outward convection of the cosmic rays by the supersonic solar wind, the diffusion of cosmic rays in the ever-present irregularities in the solar heliospheric magnetic field, and adiabatic energy changes (e.g. see Fisk 1979, 1980). Recently, a fourth term has been re-examined which represents the drifts of the cosmic rays in the large-scale magnetic field and especially in the vicinity of the current sheet which divides the heliosphere into two hemispheres containing oppositely directed fields e.g. along the Parker spiral toward the Sun in the north and away from the Sun in the south (Jokipii et.al. 1977; Isenberg and Jokipii 1978, Jokipii and Kopriva, 1979).

Great changes occur in the structure of the heliospheric magnetic field during the course of the sunspot cycle. Near minimum the current sheet the boundary between magnetic field toward and away from the Sun, is nearly equatorial with four small excursions away from the solar equatorial plane in each rotation. Since the ecliptic plane is tilted only 7.25° to the solar equator, even these small 10°-15°excursions are large enough to affect the Earth and produce the four sector structure commonly observed in the interplanetary magnetic field (IMF) near minimum (Svalgaard and Wilcox, 1975).

There is now growing awareness that solar cycle related changes in the large-scale structure of the heliospheric current sheet may play an important role in the modulation of galactic cosmic rays. To date attention has been focussed on the configuration of the current sheet at times near solar minimum when the current sheet structure is relatively simple. Previous analyses have explored the effect on cosmic ray intensities of a single current sheet which is tilted with respect to the heliographic equator under the assumption that the tilt of the current sheet is a minimum at a solar minimum and increases as solar maximum approaches (Thomas et.al. 1986).

The latitudinal variation in the intensity of the galactic cosmic rays with respect to the heliographic current sheet is an indicator of the relative importance of particle drifts and diffusion in heliospheric propagation. Symmetries in the interplanetary magnetic field due to the Sun's rotation i.e. warped up spiral field lines at the equator in contrast to nearly radial field lines at either pole, should result in a latitudinal organisation of the flux about the heliographic equator (Fisk, 1976; Newkirk and Fisk, 1985). Badruddin et.al. (1985) demonstrated that cosmic ray intensity generally decreases with increasing time from current sheet encounters and interpreted this as indicative of latitudinal variation.

Cosmic ray intensity variations near the heliospheric current sheet - both above and below it - have been studied during 1964 - 1976 (i.e. in 20th solar cycle). In this analysis we have used the data from neutron monitors well distributed in latitude over the Earth's surface. First this study has been made during the two solar activity minimum periods (1964 - 1965) and (1975 - 1976). We have also analysed the data by dividing the whole solar cycle 20 period according to the changes in solar activity, interplanetary magnetic field polarity and coronal holes. All these studies have shown a negative gradient with respect to the current sheet. These results have been discussed in the light of theoreitcal and observational evidences. Suggestions have been given to over -come the discrepancy between the observational and theoretical results. Further, possible explanations for these observational results have been suggested.

In light of the apparent importance of temporal variations in cosmic ray modulation there has been surprisingly litle recent theoretical work on time dependent cosmic ray transport. Early theoretical work had established the fundamental physical processes of importance.

Recently, a special model of a Forbush decrease based on convective - diffusive transport and a linear sink cf particles propagating through the solar wind was suggested by Bland (1976). Morfill et.al. (1979) computed the spatial diffusion coefficient expected in a fast and in a slow stream and in the intervening corotating interaction region and derived corotating 27-day variation profiles based on the azimuthal variation of the diffusion coefficient in essential agreement with neutron monitor observations. Thomas and Gall (1982, 1984) have performed Monte Carlo calculations of particle transport in the enhanced magnetic fields associated with corotating interaction regions and propagating interplanetary shocks.

Finally Nishida (1982, 1983) has performed thorough and detailed numerical calculations of Forbush decreases based on enhanced scattering and solar wind speed behind a propagating shock wave for both the convection - diffusion equation and the full transport equation including energy dependence. His calculated profiles bear a striking resemblance to observed profiles, including energy dependent precursor, decrease and recovery. More recently Kadokura and Nishida (1986) extended the calculations of Nishida for two dimensional heliosphere for magnetic storms including the direction (positive or negative) of the interplanetary magnetic field and particle drift.

More recently Chih and Lee (1986) have provided a simple but systematic analytical framework for treating time-dependent problems in cosmic rav modulation. Their theory is perturbation theory based on linearizing the standard transport equation in temporal variations (solar wind velocity, drift velocity or spatial diffusion tensor corresponding to transient solar wind conditions) of the transport coefficients and the resulting cosmic ray response. Although a perturbation approach cannot replace the fine numerical work of Nishida (1982, 1983) and Kadokura and Nishida (1986) which is well suited to the large-amplitude variations observed and a realistic spatial and energy dependence of the transport coefficients, it does provide a conceptual generality, simple analytical expressions, reproducibility, and perhaps even physical insight not possible in numerical work.

The trend in recent theoretical studies of cosmic ray propagation in interplanetary space has been to emphasize the diffusive motion of particles through random microscale fluctuations in the interplanetary magnetic field which are assumed to be homogeneous or at most spherically symmetric. While having the merit of theoretical simplicity, such an approach ignores the meso-scale structure of the interplanetary magnetic field, which is largely the result of stream dynamics. The importance of mesoscale interactions was recognised in early theoretical studies (Parker, 1963) but was based largely on speculations about the magnetic field configurations. Now the long-term 'in-situ' measurements of the plasma and magnetic field by two or more spacecraft and improvement in our knowledge of the dynamics of the streams provide a basis for a deeper understanding of the effects of the interplanetary medium on cosmic rays.

Isolated corotating and transient flows are associated with short-term depressions in cosmic ray intensity, but the effects are localized in longitude. Systems of corotating streams donot produce a long term modulation effect, although temporary, short term depressions in cosmic ray intensity are associated with individual streams and interaction regions. The long term modulation in cosmic rays inside 1 AU is associated with turbulence in transient disturbances that probably encompass a large longitudinal extent around the Sun. In mixed flow systems the effects are intermediate between those of corotating and transient systems. The net modulation may be relatively small, with large short-term variations associated with individual streams (Burlaga et.al. 1986).

Sharp temporary decreases of the galactic cosmic radiation of a duration of several days and an amplitude of a few percent have been observed and studied for many years. Although it is generally agreed that these Forbush decreases are caused by magnetic field variations associated with interplanetary disturbances, there remains considerable disagreement as to the configuration responsible. Among the many observational features of cosmic ray variations, which a theory of cosmic ray propagation should explain, Forbush and similar decreases at neutron monitor energies appear to be conceptually the simplest. The 11-year modulation may well have its cause in some region of space inaccessible as yet to observation, and solar flare events have the possible complication of the influence of the acceleration process or solar conditions.

One of the problems to be solved in theory of Forbush decreases is the isolation of the specific factor in the interplanetary medium which is causing the phenomenon. In the review article by Lockwood (1971) a number of possible causative agents of Forbush decreases are discussed and the merits of each model are shown. Barouch and Burlaga (1975) have argued the case for regions of high magnetic field ('blobs') being the main cause. However, because of the well known association of high fields with disturbed conditions, they have been unable to demonstrate unambiguously that the strength of the field rather than the amplitude of the fluctuations was causing the decreases.

It is known that the interplanetary medium in the period approaching solar maximum is characterised by an enhancement in the occurrence of transient solar wind streams and shocks (Burlaga et.al, 1984, Smith, 1983) and that such systems are often associated with loop like magnetic structure or clouds (Klein and Burlaga, 1982; Burlaga et.al. 1982).

The mechanism responsible for the particle events associated with the passage of the interplanetary shock waves have received much theoretical and experimental attention (Axford, 1981; Sanderson et.al. 1985).

The bulk flow properties of the solar wind are perhaps the most obvious indicators of the existence of large-scale structure. A fast solar wind stream overtakes a slower stream producing an interaction region into which material flows from both sides. At the leading edge of this region, slower material is swept up, compressed, heated and accelerated. At the trailing edge, material from the fast stream flows in and is compressed, heated and decelerated. A pair of shocks may develop at these edges (Whang, 1984). Across the contact surface produced by the collision or merging process, the flow velocity and the total pressure remain continuous, but the temperature, the plasma density and the magnetic field are continuous. At large helio-centric distances, shocks belonging to neighbouring streams also interact with one another. These interactions play very important roles in the dynamical evolution of large-sacle inter-planetary structures. They can significantly modify the structure of the solar wind.

Interplanetary shocks are characterised by simultaneous, well defined discontinuties in solar wind bulk velocity, density, temperature and magnetic field strength. The sense of these jumps (positive or negative) depends on whether a given shock is propagating away from or toward the Sun in the solar wind rest frame.

As has been pointed out recently by Jokipii (1986) drifts along the shock front and in the IMF can affect the spectrum and the spatial distribution of particles at the termination shock. When drifts are downward from the poles, they are poleward along the shock front. Both effects tend to limit the shock acceleration of particles that are injected near the poles. Conversely, when the drifts are towards the poles in the IMF, as they are in the current cycle (cycle 21), the drifts are downward from the poles along the shock front. These effects will increase the number of times particle interact with the shock, thereby increasing the energy they can gain, and will spread particles injected over the poles towards the equatorial region. All known transport effects, including energy change (both acceleration at the shock and adiabatic cooling), diffusion, convection and gradient and curvature drifts (at the shock and in the wind) have been included in a two dimensional model heliosphere (Jokipii, 1986). The results show encouraging agreement with observations, including recent observations of the change in energy spectrum as the sign of the interplanetary magnetic field changed during the last sunspot maximum.

Borrini et.al. (1982) have analysed all the interplanetary shock wave disturbances detected by instruments on IMP 6,7 and 8 from 1971 through 1978. The hourly intervals of the passage at Earth of 103 forward shocks were accepted as the zeroth hour for a superposed epoch analysis using the pressure corrected hourly counting rate of the Deep River neutron monitor. The result of this superposition does not show a preshock increase (Ankiewicz et.al. 1983) as would be expected from plane, steady state shock wave solutions, and as is seen from satellite recordings at low particle energies. A strong Forbush decrease sets in at the shock time, confirming the convective, effect of the passsing shocks. It is suggested that these steplike changes are caused when cosmic rays are accelerated by a series of outward moving shock waves during transport of the cosmic rays from the heliospheric boundary to Earth (Ankiewicz et.al. 1983).

Iucci et.al. (1981, 1984) showed that the front edge perturbation 'strength' made up by the shock and magnetic blob effects, is well correlated (Correlation Coefficient, 0.96) with the observed Forbush decrease amplitude. Therefore if the shock is almost symmetrical about the flare longitude, the asymmetry of the Forbush decrease modulated region is likely to be due to the magnetic perturbation following the shock, which should be displayed asymmetrically in longitude, as suggested by Haurwitz et.al. (1965).

Barnden (1973) found that the descending phase of some Forbush decrease exhibits a clear two-step structure which is located inside the associated interplanetary disturbance. The magnetic field intensity and solar wind plasma parameters indicate that the first step begins with the shock passage on the Earth (Iucci et.al. 1984, Barnden, 1973), the second step occurs generally near a discontinuity located inside the magnetic blob and followed by the flare ejecta or driver gas. This second decrease can be often connected to the entry of the Earth into a region with loop-like magnetic field configuration (Zwickle et.al. 1983).

The asymmetric second step of Forbush decreases may be due to the longitudinal asymmetry of the magnetic perturbation following the shock (Haurwitz et.al. 1965; Akasofu and Yoshida, 1967). The magnetic field compression produced by a nearly symmetric shock, sustained by the driver gas and expanding into the Archimedean interplanetary magnetic field, will be more pronounced somewhere in the west of the flare's meridian plane, but not too far from this plane on which the shock exhibits the highest velocities.

The most commonly used characteristics in determining the presence of driver gas behind interplanetary shocks are the abundance enhancements and proton temperature depressions. However, these plasma signatures are observed after less than half of all shocks (Schwenn et.al., 1980, Borrini et.al. 1982) and when present can show a very complex pattern (Ogilvie and Burlaga, 1974; Bame et.al. 1979).

The existence of ordered interplanetary field configurations with a radial dimension of the order of 0.25 AU at 1 AU., characterised by higher than average field strengths and a rotation of the field vectors parallel to a plane, was demonstrated by Burlaga and Klein (1980) and Burlaga et.al. (1981) who called them 'magnetic clouds'. A statistical study of magnetic clouds at 1 AU showed that during the period from 1967 to 1978, they occurred at the rate of at least one every three months and that there average radial dimension was 0.25 AU (Klein and Burlaga, 1982).

In the field of transient variations correlation studies between cosmic ray measurements at 1 AU and other heliocentric distances and characteristic parameters of the interplanetary medium (e.g. solar wind speed, intensity and direction of the IMF etc.) and specially with specific types of interplanetary perturbations (e.g. shock associated clouds, stream interfaces, cold magnetic enhancements, etc.) have been very successful in yielding new knowledge about the structure of these modulating perturbations as well as their evolution in space and time. Experimental evidence has been found for substantial differences in the effects of the various types of interplanetary perturbations on cosmic rays and for a dependence of these effects on the three dimensional configuration of the interplanetary medium. More of these studies are needed especially in order to explain the physical process involved (Fluckiger, 1985).

We have investigated the influence of three classes of magnetic clouds - shock associated cloud, stream interfaces and cold magnetic enhancements - On cosmic ray intensity. We have found that the Forbush decrease associated with shock - associated clouds shows a distinct two step decrease. The first step begins with the shock passage at the Earth. The second step is connected to the entry of the Earth into a region with an enhanced magnitude of the interplanetary magnetic field with a loop-like field configuration. This conclusion is in agreement with the results obtained by Badruddin et.al. (1986) for the Forbush decreases associated with shock - associated clouds.

To a larger extent, these studies related to magnetic clouds should also include anisotropy effects, they should definetely include the rigidity range above 10 GV and they should be extended to all three dimensions of interplanetary space (Fluckiger, 1985).

To study the diurnal anisotropy during the passage of these clouds and interplanetary shocks over the Earth, we need a suitable technique to calculate diurnal amplitude and phase. Since the Forbush decreases are associated with these clouds and interplanetary shocks, the simple harmonic analysis technique which gives diurnal amplitude and phase cannot be applied. It is also known from the existing literature that none have tried to find out the diurnal amplitude and phase during the passage of such specific type of perturbations and interplanetary shocks. The study of these will give full account of the structure of the interplanetary modulating perturbations. Hence to separate temporal world-wide decreases and diurnal variations from the neutron monitor time record, we have developed a suitable technique which is discussed in detail in Chapter II. We have calculated the diurnal amplitude and phase during the passage of such specific perturbations i.e. three types of magnetic clouds and interplanetary shocks over the Earth.

Studies of the heliolatitudinal distribution of cosmic rays have been made by many researchers to obtain informations about the three dimensional picture of the physical conditions in the interplanetary space. There may be two methods to detect the cosmic ray distribution perpendicular to the ecliptic plane using cosmic ray measurements on the Earth. One is to use the Earth's excursion of $\pm$ 7.25^{o} in heliolatitude in the course of the year (Antonucci et.al. 1978, 1985 and references therein). The other method is to use the cosmic ray flow in the ecliptic plane arising from $\vec{B} \times \vec{\nabla} U$ ($\vec{B}$ is the interplanetary magnetic field (IMF) vector and $\vec{\nabla} U$ is the density gradient perpendicular to the ecliptic plane). If $\vec{B}$ lie in the ecliptic plane, the direction of this flow is perpendicular to $\vec{B}$ and depends on the sense of $\vec{B}$. This flow will be superposed on the so-called corotation streaming. This steaming obtained from $\vec{B} \times \vec{\nabla} U$ is connected with the regular spiralling motion in the magnetic field. It is not directly connected to particle drift. Without density gradient, drift will not produce any anisotropy, while a density gradient does lead to a streaming in a homogeneous magnetic field, too. Yoshida et.al. (1973) observed that high anisotropy during Forbush decreases required the density gradients that are transverse to the magnetic field and these have magnitude of the order of 10-20 times the quiet time gradients.

Enhancements of the grad $\vec{B}$ drift have also been detected during the Forbush decrease (Yoshida et.al. 1973 and Suda et.al., 1981). Being dependent on IMF polarity which is toward or away, the transport by the particle density gradient drift should bring cosmic rays towards the ecliptic plane. The $\vec{B} \times \vec{\nabla} U_p$ streaming adds a polarity dependent component to the diurnal variation in solar time.

In the case of specific type of perturbations such as magnetic clouds (shock associated, interface associated and cold magnetic enhancements) and interplanetary shocks with driver gas the drift velocity is produced due to grad - $\vec{B}$ which is vary large. Due to this large drift velocity redistribution of cosmic ray density perpendicular to the ecliptic plane is established. This density gradient perpendicular to the ecliptic plane produces a flow due to $\vec{B} \times \vec{U}$ term in the ecliptic plane which adds to the diurnal component depending upon the sign of $\vec{B}$ (i.e. magnetic field of the front boundary of the clouds). This streaming has been considered to explain our (Yadav et.al. 1987) results of diurnal amplitude and phase related to three categories of clouds. Yadav and Badruddin (1983) showed that diurnal amplitude for the period 1972-1976 (IMF polarity away, +) is large than for the period 1964-1968 (IMF polarity towards, -) and phase shifts to earlier hours. Ostman et.al. (1969) showed distinct phase shift and increase in diurnal amplitude in the period of enhanced solar activity accompanied by moderate disturbances of the geomagnetic field.

CHAPTER II

A TECHNIQUES TO STUDY THE COSMIC RAY ANISOTROPY DURING THE DAYS OF FORBUSH DECREASES

2.1 INTRODUCTION

The world-wide temporal decreases in galactic cosmic ray intensity are known as Forbush decreases after their first observation made by Forbush in 1937. Many of their specific features have been established and reviewed by Lockwood (1971).

Despite in considerable progress in observing and interpreting the specific features of Fds, conclusions concerning the variations of the anisotropy during Forbush decreases are not much comprehensive. There are Forbush decreases which have enhanced daily variation during their recovery period. We must remember the fact that sometimes the decrease is much greater than the amplitude of diurnal or other local variations which superpose on the world-wide decrease. Therefore, the diurnal variation simply derived from the superposed intensity is more or less deformed due to the curvature of the time variation curve of the world-wide decreases. During the last phase of cosmic ray storm or Forbush decrease, when the curvature is relatively small, the deformation is not so large, but at the beginning and during the main phase of cosmic ray storm or Forbush decrease, when the curvature is very large, the world-wide decrease and local time variation deform each other. The nature of the diurnal and semi-diurnal anisotropy during the

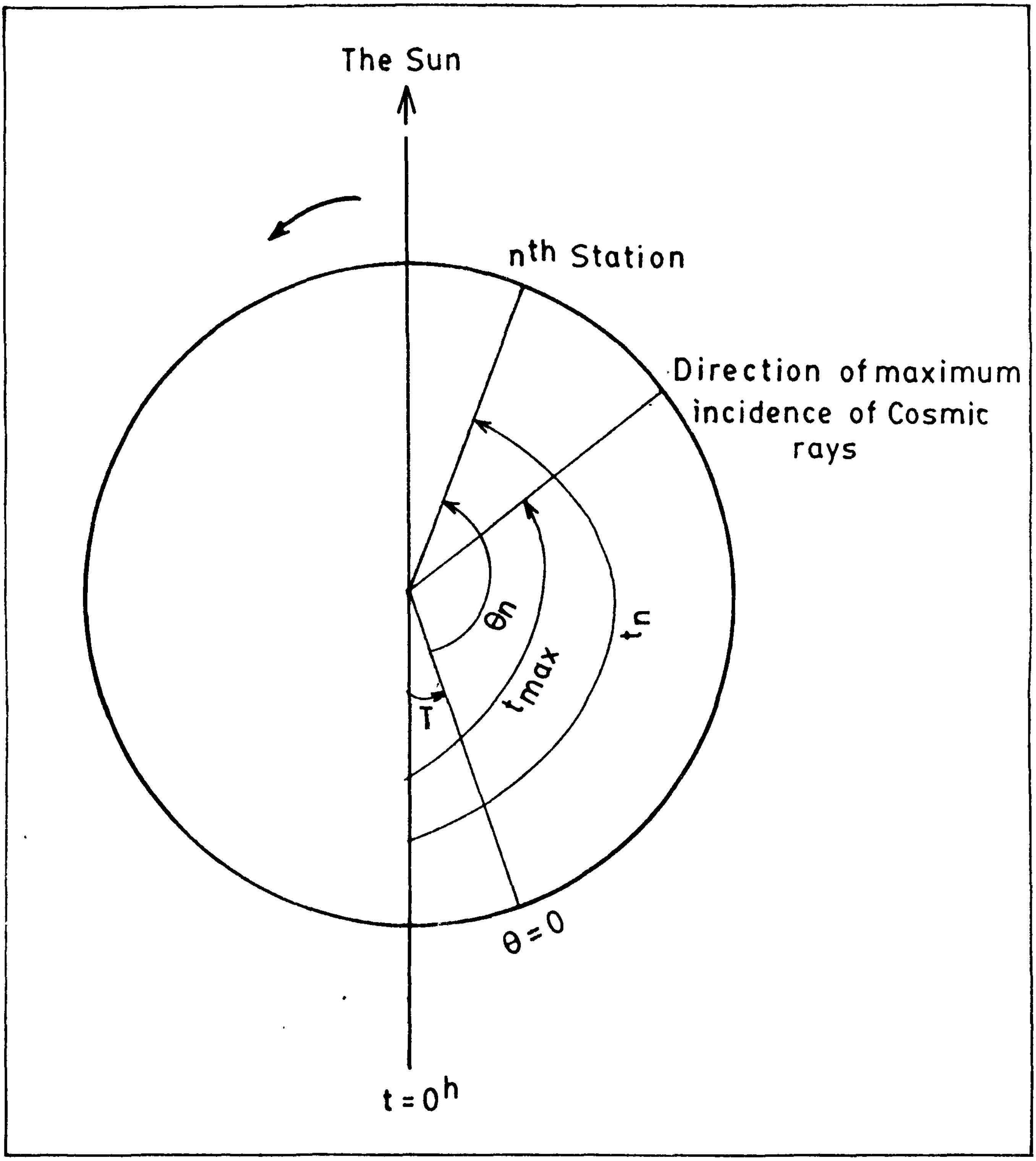
Fds have not yet been studied thoroughly and systematically. In the early investigations of large Forbush decreases, a shift in the time of maxima towards earlier hours and a noticeable increase in the amplitude of daily variation during and after Fds have been observed (Dorman, 1963). Due to the presence of characteristically large anisotropy and high variation of Fds both in time and space, it is difficult to evaluate the rigidity modulation of cosmic ray intensity during Fds. In order to get better information about the solar time variation at the time of magnetic storm or Forbush decrease, we have to find out a method to know the world-wide variation and local variation separately.

2.2 SEPARATION OF WORLD-WIDE AND LOCAL TIME VARIATION

Separation of the diurnal variation from world-wide intensity-time variations can be accomplished by a method introduced by Sekido et.al. (1952). He assumed that neglecting any differences in the solar time variation and in the primary energies due to differences in latitude, and types of detectors, the cosmic ray intensity corrected for barometer, $I_n(T)$ observed at some station n at Greenwich mean time T (Fig. 2.1) may be expressed as follows:

$$I_n(T) = k_n f(T) + a(T) \, \mathrm{Cos} \, (t_n - t_{max}(T)) + A_n(T)$$

where, k_n = normalizing factor for nth recording station which is constant and is nearly equal to unity



2.1 The cosmic ray intensity observed at any n^{th} station.

f = World-wide variation (decrease)

a = amplitude of diurnal variation

t_n = local time = $T + \theta_n$

θ_n = longitude of the nth station

t_{max} = local time of diurnal maximum

A_n = local variation of intensity with periods of longer than one day due to atmospheric effects i.e. long term variation of intensity.

For the determination of f, a and t_{max} as solutions of simultaneous equations given above, N(number of stations) ≥ 3 is a sufficient condition provided $A_n(T)$ is obtained through successive approximation method. If $N = 1$ we can get only the day to day change of approximate values of a and t_{max}. But if we can use sufficiently large N, the hourly values of a and t_{max} will be obtained to show when the amplitude increase and the phase advancement begin.

This method is based upon the assumption that the diurnal variation will be eliminated in the sum of the normalized records from three stations with a longitude separation of approximately 120^{o} and with comparable characteristics as concerns threshold rigidities and distributions of acceptance cones.

There are certain difficulties to be over-come in practical applications of this method (Rao, 1963). For instance a very limited number of stations fulfil the necessary conditions. However the method can easily be changed so as to include any number of stations inside a given region of threshold rigidities (Sandstrom, 1968). As in the original method the hourly or bihourly records have to be normalized to one and the same interval of nx24 hours. The weights w_i are then applied to the separate records according to the conditions

$$\Sigma W_i = 1$$

$$\Sigma W_i A_i \text{ Sin } \phi_i = 0$$

$$\Sigma W_i A_i \text{ Cos } \phi_i = 0$$

A_i are the amplitudes of the diurnal variations which can be equal for stations with very similar instrumental characteristics and can be determined by harmonic analyses over periods with no world-wide variations or computed from the distributions of acceptance cones and particle trajectories in other cases. In the first approximation ϕ_i will be the longitudes of the stations. Further refinements demand that ϕ_i include the phase differences due to the time corrections for the individual stations.

After application of proper weights we compute the means of the normalized simulatneous records. Provided that, during a world-wide event any changes of phase amplitude are simultaneous and proportional at all stations, the resulting means will describe the world-wide intensity time variations.

The assumptotic cone for Alert is almost fixed in space as the earth rotates, and for the other stations covers a fair range of longitudes in the celestial sphere. In Fig. 2.2 the complete absence of 24 hour period (diurnal) variation at Alert is apparent, confirming both the assumptotic cone prediction and the absence of a diurnal wave noted by visual inspection of the time recordings (Bachelet et.al. 1968).

The practical absence of the diurnal effect in the time recordings of the Alert supermonitor, (Steljes, 1966) clearly showing the presence even of small-scale intensity perturbation, provided us with the possibility of investigating the time correlation of cosmic ray events at the Earth and in space. This allows us to develop a technique to separate the isotropic and anisotropic part in the time variation for each station (Yadav and Rana, 1983)

2.3 MATHEMATICAL TREATMENT

The pressure corrected hourly cosmic ray intensity during the Fd days for any nth recording station can be expressed as (Sekido, 1952)

$$I_n(t) = k_n f(t) + Y_n(t) + L_n \qquad \ldots\ldots (1)$$

where k_n = the normalizing factor for nth recording station and is nearly equal to unity.

$f(t)$ = The world-wide component of decrease which is zero during normal days

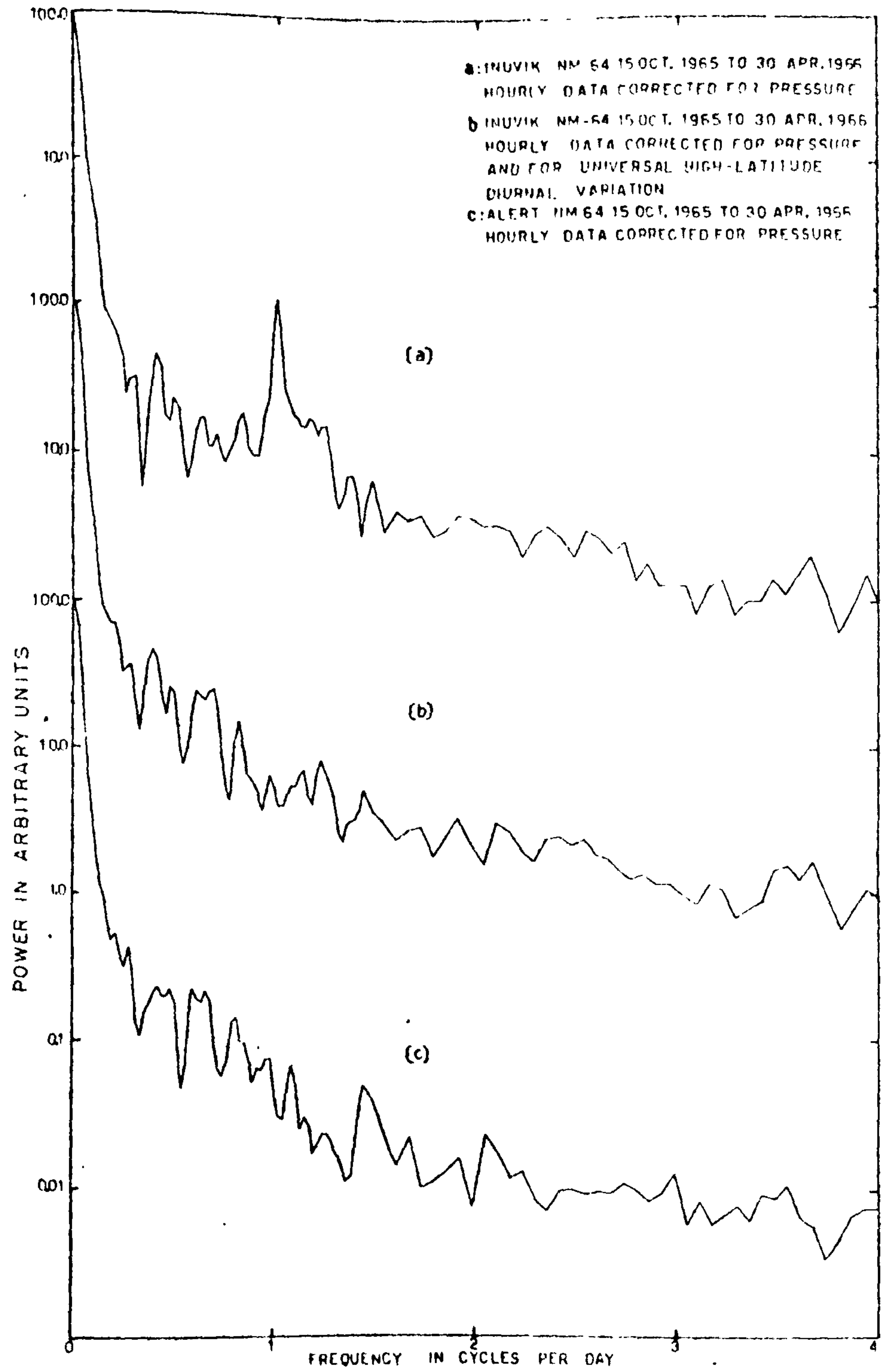


Fig. 2.2 Power spectra in arbitrary units of hour neutron monitor intensity.

t = varies from 0 to 24 hours

L_n = component of cosmic ray intensity corresponding to long term variation which is generally very small compared to world-wide component of decrease, $f(t)$

$Y_n(t)$ = The hourly values of cosmic ray intensity which are responsible for daily variation.

This part of daily variation i.e. $Y_n(t)$ can be expanded with the help of Fourier series in the following manner

$$Y_n(t) = A_{n_o} + \sum_{k=1}^{n} A_k \text{ Cos } kwt + \sum_{k=1}^{n} B_k \text{ Sin } kwt \quad .... (2)$$

Taking the mean of daily values, we can write equation (1) as:

$$\frac{1}{24} \Sigma\, I_n(t) = \frac{1}{24} \Sigma\, [k_n f(t) + Y_n(t) + L_n]$$

$$\text{or } \frac{1}{24} \Sigma\, I_n(t) = \frac{1}{24} \Sigma\, k_n f(t) + \frac{1}{24} \Sigma\, A_{n_o} + \frac{1}{24} \sum_{k=1} A_k \text{ Cos } kwt$$

$$+ \frac{1}{24} \sum_{k=1} B_k \text{ Sin } kwt + \frac{1}{24} \Sigma\, L_n$$

$$\text{or } I_n(d) = k_n f(d) + \bar{A}_{n_o} + \bar{L}_n$$

$$\text{or } I_n(d) = k_n f(d) + \bar{A}_n \quad .... (4)$$

$$\text{where } \bar{A}_n = \bar{A}_{n_o} + \bar{L}_n$$

It has been established (Bachelet et.al. 1968) that for polar stations like Alert (82.5^{o} N, 62.5^{o} W) having zero cut off rigidity the cone of acceptance is almost fixed in space as the earth rotates and the daily variation be practically absent. Thus for such a station the cosmic ray intensity for any t^{th} hour can be expressed as

$$I_a(t) = k_a f(t) + A_{a_o} + L_a \qquad \ldots\ldots (5)$$

Taking its daily mean values, we have

$$I_a(d) = k_a f(d) + \bar{A}_a \qquad \ldots\ldots (6)$$

where

$$\bar{A}_a = \bar{A}_{a_o} + \bar{L}_a$$

For normalizing the world-wide component at Alert when even very low rigidity particle reach the ground level detector. Assuming $k_a = 1$ and putting this value in equation (6) we have

$$I_a(d) = f(d) + \bar{A}_a$$

or

$$f(d) = I_a(d) - \bar{A}_a \qquad \ldots\ldots (7) \text{ for Alert}$$

From equation (4)

$$k_n f(d) = I_n(d) - \bar{A}_n \qquad \ldots\ldots (8) \text{ for } n^{th} \text{ station}$$

Dividing equation (8) by equation (7), we will have

$$k_n = \frac{I_n(d) - \bar{A}_n}{I_a(d) - \bar{A}_n} \qquad \ldots\ldots (9)$$

Thus the value of k_n, the normalizing factor, can be determined by this equation no.(9) for the n^{th} recording station.

Putting $k_a = 1$ and $\bar{A}_a = \bar{A}_{a_o} + L_a$ the equation (5) can be expressed as

$$I_a(t) = f(t) + \bar{A}_a$$

or $$f(t) = I_a(t) - \bar{A}_a \qquad \text{..... (10)}$$

Equation (1) can be written as

$$Y_n(t) + L_n = I_n(t) - k_n f(t) \qquad \text{..... (11)}$$

Putting the value of k_n and $f(t)$ from equation (9) and (10) in equation (11), we will have

$$Y_n(t) + L_n = I_n(t) - \frac{I_n(d) - \bar{A}_n}{I_a(d) - \bar{A}_a} [I_a(t) - \bar{A}_a] \qquad \text{..... (12)}$$

Thus the normal cosmic ray intensity for any t^{th} hour superimposed with long term variation can be evaluated from equation (12). From these hourly values of cosmic ray intensity, the long term variation (L_n) can be filtered either by applying the trend correction (Yadav and Naqvi, 1973) or by taking moving averages. The trend-corrected data so obtained may be subjected to harmonic analysis (Yadav and Naqvi, 1973), which will yield the amplitudes and phases of diurnal and semi-diurnal anisotropies during the period of Forbush decreases.

Furthermore, the hourly values of the world-wide component f(t) evaluated from equation (10) will give an exact shape of Fd through which various features of Fds can be studied. Thus this technique has a two fold importance. Firstly it provides a method to study the nature of cosmic ray anisotropy during Fd days and secondly it gives an almost exact shape of Fd profiles.

2.4 PROCEDURE FOR THE APPLICATION OF THE TECHNIQUE

2.4.1 Calculation of $\bar{A}_a$ and $\bar{A}_n$

This is the constant level of cosmic ray intensity. By visual inspection on the plots of cosmic ray intensity variation all those days having Forbush decreases, transient decreases, ground level enhancement and any abnormal behaviour are subtracted from the time record of the month of a particular year for Alert or any polar station. Then the mean of remaining days of that month for that year is calculated. It is $\bar{A}_a$ for our use.

The same procedure may be applied to any other station whose data has to be used for calculation and the value of $\bar{A}_n$ is calculated. In our case we have calculated these values for Alert and Deep River neutron monitoring stations which are given in table 2.1.

2.4.2 Calculation of Forbush decreases

This can be calculated with the help of equation number 10.

Table 2.1 For the Determination of $\bar{A}_a$ and $\bar{A}_n$

Year	Station \ Month	January	February	March	April	May	June	July	August	September	October	November	December
1966	Alert	7692.6	7682.4	7698.4	7516.0	7512.1	7466.6	7421.3	7409.9	7165.6	7266.2	7301.3	7246.7
	Deep River	7083.7	7063.6	7084.8	6968.8	7024.2	6907.9	6868.6	6865.9	6686.3	6801.4	6816.4	6774.4
1967	Alert	7179.6	7193.8	7197.3	7194.8	7185.2	7092.8	7130.6	7036.6	7014.3	7067.9	6977.0	6936.0
	Deep River	6703.1	6706.7	6721.6	6761.7	6777.4	6632.5	6683.9	6604.3	6618.1	6661.9	6608.3	6574.1
1968	Alert	---	---	6982.0	7030.2	6909.7	6882.0	6880.1	6780.2	6743.5	6770.3	6603.0	6600.3
	Deep River	6620.6	6604.5	6572.3	6649.0	6559.6	6485.2	6491.9	6457.0	6442.7	6419.2	6278.9	6249.1
1969	Alert	6735.5	6810.9	6800.2	6763.3	6752.7	6661.3	6742.4	6860.7	6694.2	6717.1	6739.4	6741.0
	Deep River	6384.7	6438.6	6450.1	6434.5	6234.7	6118.1	6194.5	6300.0	6383.7	6413.4	6432.7	6415.9
1970	Alert	6700.6	6793.2	6809.1	6664.7	6661.8	6546.8	6619.0	6639.2	6698.7	6746.8	6719.2	6830.4
	Deep River	6419.1	6453.6	6502.6	6369.6	6385.6	6246.6	6293.9	6333.7	6414.4	6471.0	6455.7	6548.7
1971	Alert	6808.5	6920.4	6907.0	6960.0	7059.2	7121.9	7154.5	7188.5	7149.8	7318.9	7577.7	7541.8
	Deep River	6530.9	6628.9	6653.9	6705.8	6777.5	6855.4	6884.5	6916.2	6874.8	6996.6	7046.0	6983.7
1972	Alert	7514.1	7496.6	7550.8	7560.1	7529.3	7388.1	7484.4	7278.9	7438.1	7475.1	7508.1	7485.0
	Deep River	6964.7	6961.6	6998.6	7037.8	7036.9	6907.6	6973.4	6781.0	6946.9	6995.4	7038.0	6972.6
1973	Alert	7509.9	7491.9	7388.8	7269.2	7300.9	7317.6	7391.5	7461.8	7538.9	7481.1	7515.8	7543.6
	Deep River	7017.5	7022.3	6907.8	6815.9	6844.1	6857.7	6930.4	6992.5	7067.4	7070.2	7085.7	7038.6
1974	Alert	7561.1	7590.4	7503.1	7451.8	7338.4	7237.4	7163.7	7261.7	7241.8	7161.5	7213.2	7353.8
	Deep River	7030.2	7073.1	6993.1	6964.1	6859.3	6759.8	6687.1	6760.1	6783.8	6736.1	6770.3	6882.0
1975	Alert	7386.2	7431.3	7451.2	7492.7	7496.4	7507.1	7540.2	7509.8	7503.3	7491.1	7433.5	7482.8
	Deep River	6902.5	6951.1	6972.6	7031.0	7040.3	7064.2	7059.1	7022.1	7032.9	7023.0	6970.8	7011.8
1976	Alert	7479.5	7518.7	7544.0	7466.4	7486.1	7490.0	7545.1	7548.0	7539.5	7514.8	7545.3	7521.4
	Deep River	7016.6	7023.3	7057.9	7021.7	7049.5	7046.3	7077.9	7089.0	7098.1	7099.9	7104.2	7086.97
1977	Alert	7482.1	7499.0	7512.2	7515.7	7499.1	7468.3	7375.1	7402.2	7492.6	7472.0	7517.8	7532.1
	Deep River	7085.6	7058.2	7068.9	7082.3	7080.4	7051.3	6926.4	6953.6	7027.0	70[illegible].5	7075.0	7075.3
1978	Alert	7434.9	7397.4	7384.5	7165.2	7251.1	7245.7	7243.7	7377.9	7378.6	7200.5	7309.6	7279.6
	Deep River	6977.5	6957.15	6948.0	6760.5	6835.4	6833.5	6804.6	6929.4	6949.7	6908.9	6875.9	6874.2

We have to feed the hourly counts of Alert and the constant $\bar{A}_a$ from table 2.1 for the particular month of that year in the computer programme which has been developed by us. This way hourly values of Forbush decrease are obtained.

2.4.3 Calculation of $Y_n(t)$ Responsible For Diurnal Variation

By feeding hourly values of any n^{th} station and $\bar{A}_a$ from table 2.1 (in our case Deep River) in the computer program with the help of equation number 12, we can calculate the hourly values of that station which are responsible for the diurnal vairation. The value of normalizing factor k_n is calculated in the same computer program with the help of equation number (9).

2.4.4 Calculation of Diurnal Amplitude and phase

These hourly values obtained above for any n^{th} station are subjected to harmonic analysis which is discussed in this Chapter in the following pages.

All these calculations have been done with the help of computer program. This way we can calculate amplitudes and phases of diurnal and semi-diurnal anisotropy.

2.5 HARMONIC ANALYSIS

Any single valued, periodic, continuous and finite function can be expressed by a Fourier series of the type

$$Y = f(x) = a_o + \sum_{n=1}^{n} a_n \text{ Cos } nx + \sum_{n=1}^{n} b_n \text{ Sin } nx$$

This function is periodic and has the period 2π and

a_o, a_1, a_2 .... b_1, b_2, b_3 .... are called the Fourier coefficients and are independent of x.

The process of determining the Fourier coefficients (i.e., the values of a_o, a_1, a_2, a_3 .... b_1, b_2, b_3 ....) of a given function is called HARMONIC ANALYSIS (or Fourier analysis). According to Perry (1898) and with the help of trigonometric formulae the coefficients a_o, a_1 ... a_n, b_1, b_2 .... b_n of above equation are given as

$$a_o = \frac{1}{2\pi} \int_o^{2\pi} f(x)dx = \frac{1}{2\pi} \int_o^{2\pi} Y\, dx$$

$$a_n = \frac{1}{\pi} \int_o^{2\pi} f(x) \operatorname{Cos} nx\, dx = \frac{1}{\pi} \int_o^{2\pi} Y \operatorname{Cos} nx\, dx$$

$$b_n = \frac{1}{\pi} \int_o^{2\pi} f(x) \operatorname{Sin} nx\, dx = \frac{1}{\pi} \int_o^{2\pi} Y \operatorname{Sin} nx\, dx$$

Let us expand the above series as

$$Y = f(x) = a_o + a_1 \operatorname{Cos} x + a_2 \operatorname{Cos} 2x + \ldots a_n \operatorname{Cos}(n-1)x$$

$$+ b_1 \operatorname{Sin} x + b_2 \operatorname{Sin} 2x + \ldots b_n \operatorname{Sin}(n-1)x$$

To determine the Fourier coefficients, we will make use of the experimental data which we have in our hand and this data is more than the total number of Fourier coefficients to be determined.

From the given data, it is clear that $y = f(x)$ takes the values $y_o, y_1, y_2 \ldots y_{n-1}$ when x takes the values $o, \frac{2\pi}{n}, \frac{4\pi}{n} \ldots \frac{(n-1)2\pi}{n}$ respectively.

At $x = o, \frac{2\pi}{n}, \frac{4\pi}{n} \ldots \frac{2(n-1)\pi}{n}$

then $y = y_o, y_1, y_2 \ldots y_{n-1}$

Let $n > 2r$

Now the problem is to determine $(2r+1)$ constants $a_o, a_1, a_2, \ldots a_r, b_1, b_2 \ldots b_r$

$$y_o = a_o + a_1 \text{Cos } o + a_2 \text{Cos } o + \ldots a_r \text{Cos } o$$

$$+ b_1 \text{Sin } o + b_2 \text{Sin } o + \ldots b_r \text{Sin } o$$

$= a_o + a_1 + \ldots a_r$ all other 'b' terms being zero.

$$y_1 = a_o + a_1 \text{Cos } \frac{2\pi}{n} + a_2 \text{Cos} 2 \frac{2\pi}{n} + \ldots a_r \text{Cos } \frac{(r)2\pi}{n}$$

$$+ b_1 \text{Sin } \frac{2\pi}{n} + b_2 \text{Sin} 2 \frac{2\pi}{n} + \ldots b_r \text{Sin } \frac{(r)2\pi}{n}$$

$$y_2 = a_o + a_1 \text{Cos } \frac{4\pi}{n} + a_2 \text{Cos} 2 \frac{4\pi}{n} \ldots a_r \text{Cos } r \frac{4\pi}{n}$$

$$+ b_1 \text{Sin } \frac{4\pi}{n} + b_2 \text{Sin} 2 \frac{4\pi}{n} + \ldots b_r \text{Sin } r \frac{4\pi}{n}$$

$$\vdots$$

$$y_{n-1} = a_o + a_1 \text{ Cos } \frac{(n-1)2\pi}{n} + a_2\text{Cos } 2\frac{(n-1)2\pi}{n} + \ldots a_r \text{ Cos } \frac{r(n-1)2\pi}{n}$$

$$+ b_1 \text{ Sin } (\frac{n-1}{n})2\pi + b_2 \text{ Sin } 2 \frac{(n-1)2\pi}{n} + \ldots b_r \text{ Sin } \frac{r(n-1)2\pi}{n}$$

Adding all these equations, the normal equation for a_o is therefore reduces to

$$y_o + y_1 + y_2 + y_3 \ldots y_{n-1} = na_o$$

Since all other terms are equal to zero.

Multiplying $y_1, y_2, \ldots y_{n-1}$ by 1, Cos $\frac{2\pi}{n}$, Cos 2 $\frac{2\pi}{n}$,...

Cos (n-1) $\frac{2\pi}{n}$

and adding we will get

$$y_o + y_1 \text{ Cos } \frac{2\pi}{n} + y_2 \text{ Cos } 2 \frac{2\pi}{n} + \ldots y_{n-1} \text{ Cos } (n-1) \frac{2\pi}{n}$$

$$= a_o(1 + \text{Cos } \frac{2\pi}{n} + \text{Cos } 2 \frac{2\pi}{n} + \ldots \text{Cos } (n-1) \frac{2\pi}{n})$$

$$+ a_1(1 + \text{Cos}^2 \frac{2\pi}{n} + \text{Cos}^2 \frac{2\pi}{n} + \ldots \text{Cos}^2 (n-1) \frac{2\pi}{n})$$

$$+ a_2(1 + \text{Cos } \frac{2\pi}{n} \text{ Cos } 2 \frac{2\pi}{n} + \text{Cos } \frac{4\pi}{n} \text{ Cos } 2 \frac{4\pi}{n} \ldots$$

$$\text{Cos } (n-1) \frac{2\pi}{n} \text{ Cos } (n-1) \frac{2\pi}{n})$$

....

$$a_r[1 + \text{Cos}\,\frac{2\pi}{n}\ \text{Cos}^r\ \frac{2\pi}{n} + \ldots.\ \text{Cos}\,(n-1)\,\frac{2\pi}{n}\ \text{Cos}^r(n-1)\frac{2\pi}{n}]$$

$$b_1[\text{Cos}\,\frac{2\pi}{n}\ \text{Sin}\,\frac{2\pi}{n} + \ldots.\ \text{Cos}\,(n-1)\,\frac{2\pi}{n}\ \text{Sin}\,(n-1)\,\frac{2\pi}{n}$$

$$\ldots. \qquad \ldots. \qquad \ldots. \qquad \ldots.$$

$$b_r[\text{Cos}\,\frac{2\pi}{n}\ \text{Sin}^r\ \frac{2\pi}{n} + \ldots.\ \text{Cos}\,\frac{(n-1)2\pi}{n}\ \text{Sin}^r\,\frac{(n-1)2\pi}{n}$$

Using trigonometric formulae, we know that

$$[1 + \text{Cos}^2\,\frac{2\pi}{n} + \text{Cos}^2\,2.\,\frac{2\pi}{n} + \ldots.\ \text{Cos}^2\,\frac{(n-1)2\pi}{n}\ ] = \frac{n}{2}$$

all other terms are equal to zero, thus above equation reduces to

$$y_o + y_1\,\text{Cos}\,\frac{2\pi}{n} + y_2\,\frac{4\pi}{n} + \ldots.\ y_{n-1}\,\text{Cos}\,(n-1)\,\frac{2\pi}{n} = \frac{n}{2}\,a_1$$

or

$$a_1 = \frac{2}{n}\sum_{j=o}^{j=n-1} y_j\,\text{Cos}\,j\,\frac{2\pi}{n}$$

Thus the normal equations for other constants may also be obtained and reduced in the sameway, finally we get the following set of values for a_o, a_1, a_2 ... a_r, b_1, b_2 ... b_r

$$a_o = \frac{1}{n}\sum_{j=o}^{n-1} y_j$$

$$a_1 = \frac{2}{n}\sum_{j=o}^{j=n-1} y_j\,\text{Cos}\,j\,\frac{2\pi}{n}$$

$$a_r = \frac{2}{n} \sum_{j=o}^{n-1} y_j \, Cos^r \, j \frac{2\pi}{n}$$

$$b_1 = \frac{2}{n} \sum_{j=o}^{n-1} y_j \, Sin \frac{2\pi j}{n}$$

$$b_r = \frac{2}{n} \sum_{j=o}^{n-1} y_j \, Sin^r \frac{2\pi j}{n}$$

when $r = \frac{n}{2}$, then the factor of a_r in front of the symbol Σ is $\frac{1}{n}$ not $\frac{2}{n}$

2.5.1 Application of Harmonic Analysis to Cosmic Ray and Other Branches of Physics:

The method of harmonic analysis is a very useful tool for the solar diurnal, semi-diurnal etc. Variations in the cosmic ray intensity as well as other branches of Physics such as ionosphere, solar physics and biophysics.

In the study of diurnal and semi-diurnal etc. variations our main interest is to determine their amplitudes and phases. These amplitudes and phases can also be represented on a vector diagram (known as 'harmonic dial') to study their nature and other behaviours during different periods etc.

Thus the Fourier coefficients, or we can say the amplitudes and phases of the first and second etc. harmonic components can easily be determined with the help of 24-ordinate scheme.

2.5.2 Twenty Four Ordinate Scheme:

In this scheme we have a set of 24 values of

$y_o, y_1, y_2 \ldots y_{23}$ corresponding to

$$x = o, \frac{\pi}{12}, \frac{2\pi}{12} \ldots\ldots \frac{23\pi}{12}$$

The coefficients $a_o, a_1, a_2, \ldots\ldots a_{12}, b_1, b_2 \ldots\ldots b_{11}$ of the Fourier series can be calculated with the help of the computer program developed by us.

2.5.3 Amplitudes and Phase of Harmonic Components:

With the help of the Sine and Cosine coefficients the amplitudes and phase angles can be determined by the following relation:

$$b_k = A_k \text{ Sin } \phi_k$$

$$a_k = A_k \text{ Cos } \phi_k$$

$$A_k = \sqrt{a_k^2 + b_k^2}$$

$$\phi_k = \tan^{-1} \left(\frac{b_k}{a_k}\right)$$

where A_k and ϕ_k are the amplitudes and phase of the K^{th} harmonic component. For $K = 1, 2, 3, \ldots$ etc., we have the first, second and third harmonic etc. In determining the value of ϕ_k, it is necessary that the correct quadrant be determined. In which quadrant, the value of ϕ_k lies, it depends upon the sign of a_k and b_k. The connection between the signs of a_k, b_k and ϕ_k is shown in table 2.2.Let ϕ_k is defined in terms of ϕ_k depending on the sign of a_k and b_k, by means of table 2.3

$$\Psi_k = \tan^{-1}\left(\frac{b_k}{a_k}\right)$$

Table 2.2

a_k	b_k	ϕ_k
+	+	Ψ_k
-	+	$180 - \Psi_k$
-	-	$180 + \Psi_k$
+	-	$360 - \Psi_k$

Table 2.3

+ Sin ϕ_k	+ Sin ϕ_k
- Cos ϕ	+ Cos ϕ_k
- Sin ϕ_k	- Sin ϕ_k
- Cos ϕ_k	+ Cos ϕ_k

2.5.4 Trend Correction:

In many cases, particularly in cosmic rays, the phenomenon whose variation (daily variation) is to be studied is not strictly periodic. Thus if the numbers to be analysed represent hourly means of cosmic ray intensity, the means for o^{th} hour will not in general, the same as the means for hour 24^{th}. This difference is (which on account of secular changes etc.) allowed for in practice by applying a correction (known as trend correction) to each of the terms (i.e. 24 ordinates) except that for noon. The data can be corrected in the way discussed below. Let us consider the function $y = f(x)$. Let y_o be the value of the ordinate $x = o$ (Ohr) and y_{23} is the value of the ordinate at $x = 2\pi$ (24 hr). It is found that the value of y_o is not equal to y_{23} due to the secular changes etc. Let $\bar{y}_j$ represents the trend corrected value

at $x = \frac{2\pi j}{24}$ where $j = 1, 2, \ldots 24$

y_j represent uncorrected value.

Then the trend corrected values for any hour is given by the equation

$$\bar{y}_j = y_j - \frac{(\pm \Delta y)\,(j-1)}{24}$$

where $j = 1, 2, \ldots\ldots 24$

$\pm \Delta y$ = Secular change (i.e. $\pm \Delta y = (y_{24} - y_o)$.

2.5.6 Determinations of Errors of Fourier Coefficients:

The error in the amplitude and phase of the Fourier Coefficients can be estimated by calculating the value of the standard deviation (S.D.) of the amplitude σ_{A_k} and , the S.D of the phase σ_{ϕ_k} from the experimental data. The method of calculating the values of σ_{A_k} and σ_{ϕ_k} is discussed below.

Amplitude and phase of the Fourier Coefficients are determined by 24-ordinates $y_o, y_1, y_2 \ldots y_{23}$. But in practice $y_o, y_1, \ldots, y_{23}$ or y_N in general itself are the mean values obtained from the various observed values. If $y_{I,1}, y_{I,2}, \ldots, y_{I,n}$ are the different observed values of y_I and $\bar{y}_I$ is the mean value, then σ_{y_I} is given by the relation

$$\sigma_{y_I} = \sqrt{\frac{\sum_{j=1}^{n} (y_{I,j} - \bar{y}_I)}{n}}$$

or

$$\sigma_{y_I} = \sqrt{\frac{\sum_{j=1}^{n} \delta^2_{I,j}}{n}}$$

where $\delta = (y_{I,j} - \bar{y}_I)$

where I stands for a day and $j = 1, 2, \ldots n$ and $n = 24$ in our case.

So by knowing the standard deviations of the values $y_o, y_1, y_2, \ldots y_{23}$ we can easily estimate the standard deviation of the Fourier Coefficients $a_o, a_1, a_2 \ldots b_1, b_2$ ... etc.

If Z is a linear function of $y_o, y_1, \ldots y_n$ say

$$Z = \lambda_o y_o + \lambda_1 y_1 + \lambda_2 y_2 \cdots \lambda_n y_n$$

If the standard deviations of each of the quantities y_o, $y_1, \ldots, y_n$ are $\sigma_o, \sigma_1, \sigma_2, \ldots \sigma_n$ then the S.D. of Z is given by

$$\sigma_Z = \sqrt{\lambda_o^2 \sigma_o^2 + \lambda_1^2 \sigma_1^2 + \cdots \lambda_n^2 \sigma_n^2}$$

Since $a_k = \frac{1}{12} (y_o + y_1, \ldots, y_{23})$

$$\therefore \sigma_{a_k} = \frac{1}{12} \sqrt{\sigma_o^2 + \sigma_1^2 + \cdots \sigma_{23}^2}$$

The amplitude and phase of the harmonic components are given in terms of a_k and b_k by the relation

$$A_k = \sqrt{a_k^2 + b_k^2} \qquad \phi_k = \tan^{-1} \left(\frac{b_k}{a_k}\right) \qquad \ldots\ldots (L)$$

Now, we require to know the S.D. of A_k and ϕ_k assuming that S.D. of a_k and b_k have already been calculated by the method discussed above. The standard deviation of A_k and ϕ_k can be easily calculated with the help of the principle of superposition of errors.

If a quantity Q is a function of x, y, z (say)

$Q = f(x,y,z)$, then the S.D. of Q is given by

$$\sigma_Q = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial Q}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial Q}{\partial z}\right) \sigma_z^2} \qquad \ldots. \quad (L')$$

Now using the equations L and L' the S.D. of A_k and ϕ_k is given by

$$\sigma_{A_k} = \sqrt{\left(\frac{\partial A_k}{\partial a_k}\right)^2 \cdot \sigma_{a_k}^2 + \left(\frac{\partial A_k}{\partial b_k}\right)^2 \cdot \sigma_{b_k}^2}$$

$$\sigma_{\phi_k} = \sqrt{\left(\frac{\partial \phi_k}{\partial a_k}\right)^2 \sigma_{a_k}^2 + \left(\frac{\partial \phi_k}{\partial b_k}\right)^2 \sigma_{b_k}^2}$$

$$\frac{\partial A_k}{\partial a_k} = \frac{a_k}{\sqrt{a_k^2 + b_k^2}} \quad \text{and} \quad \frac{\partial A_k}{\partial b_k} = \frac{b_k}{\sqrt{a_k^2 + b_k^2}}$$

thus we have

$$\sigma_{A_k} = \sqrt{\frac{a_k^2}{a_k^2 + b_k^2} \sigma_{a_k}^2 + \frac{b_k^2}{a_k^2 + b_k^2} \sigma_{b_k}^2}$$

from Eqn. (L)

$$\frac{\partial \phi_k}{\partial a_k} = \frac{b_k}{(a_k^2 + b_k^2)}, \quad \frac{\partial \phi_k}{\partial b_k} = -\frac{a_k}{(a_k^2 + b_k^2)}$$

$$\therefore \quad \sigma_{\phi_k} = \sqrt{\frac{b_k^2}{(a_k^2 + b_k^2)^2} \sigma_{a_k}^2 + \frac{a_k^2}{(a_k^2 + b_k^2)^2} \sigma_{b_k}^2}$$

CHAPTER III

INTENSITY VARIATION OF COSMIC RAYS NEAR THE HELIOSPHERIC CURRENT SHEET

3.1 INTRODUCTION

The comprehensive set of ground-based and spacecraft data acquired during the recent solar maximum has stimulated a renewed effort to understand the solar modulation of galactic cosmic rays (e.g. McDonald et.al. 1981, McKibben et.al. 1982). Since the discovery of modulation, a large number of explanations have been proposed. Some are qualitative suggestions, often made on the basis of correlations between cosmic rays and some aspects of solar activity. Quantitative theoretical models are also available as solutions of a transport equation for the distribution function of cosmic rays.

Since Wilcox and Ness (1965) discovered the sector structure of the interplanetary magnetic field (IMF) and their first study of the effects of sectors in the IMF upon the cosmic ray intensity, a number of other studies have been made by many authors, on the relation of IMF sector boundaries with geophysical phenomena as well as cosmic ray intensity variations. The decrease in cosmic ray intensity after the boundary passed across the Earth were pointed out by Duggal and Pomerantz (1977) from an analysis of neutron monitor data from two polar stations. These results were used to determine the radial density gradient. Recently cosmic ray intensity variations around IMF sector boundaries were studied by Fujimoto et.al. (1981). These authors found that cosmic ray density is high near the sector boundary irrespective of the IMF polarity change and interpreted this as an effect of modulation due to decrease of solar wind velocity near the boundary.

The field at the solar surface is assumed to be uniform and radial, with opposite signs on either side of a magnetic equator. This magnetic equator is a tilted plane at the Sun, which then develops into a wavy neutral sheet at larger heliocentric radii in interplanetary space. The three-dimensional magnetic field configuration of the heliosphere is of considrable importance in understanding the spatial variation of cosmic ray intensity. It appears that the Sun has a tilted dipole. Also, it has now generally been accepted that it is the rotation of the tilted dipole and of the current sheet with respect to the rotation axis of the Sun which causes the alternating polarity of the IMF observed in the interplanetary space (Schultz, 1973; Saito, 1975; Svalgaard and Wilcox, 1976; Smith et.al., 1978) rather than the so-called sector structure. Thus for a 'simple' tilted dipole, the Earth(or a fixed point in the interplanetary space) is located above the current sheet for about half the days of the solar rotation and below it for rest of the period. During the period when the solar dipole moment is directed northward, we should observe an outward directed magnetic field when the Earth is located below the current sheet (C_f Akasofu, 1982). The concept of the wobbling dipole and of the current sheet has been confirmed by Thomas and Smith (1980) by using space probe data.

The obvious difference in the total amplitude and temporal profile of the modulation of GeV (gigavolt) particles between cycles 19 and 20 has been interpreted (Shea and Smart, 1981) as reflecting sensitivity to the reversal of polarity of the heliospheric field. Many changes have been observed in the characteristic of cosmic ray modulation after the reversal of the solar poloidal magnetic field in the solar cycle 20. In order to explain such anomalies in solar modulation, many theoretical workers have incorporated in their models, a current sheet which is responsible for producing sector structure in the IMF, and the effects of gradient and curvature drifts (Jokipii et.al., 1977; Moraal et.al., 1979; Erdos and Kota, 1980). There has been, however, little discussion on the contribution that might be made to the fluxes by particles streaming into the solar system from directions perpendicular to the ecliptic plane. Mathews et.al. (1971) and Hedgecock et.al. (1972) emphasized the possible importance of the off-ecliptic control of the cosmic ray modulation and it has been suggested (Hedgecock) et.al.,1972) that galactic cosmic rays and their modulation with the solar cycle, may be more strongly influenced by latitudinal gradients than by radial gradients. Thus the evaluation of the contribution of the mechanisms, such as particle drifts (Jokipii et.al. 1977) and/or latitudinal gradients (Roelof et.al., 1981; Newkirk et.al., 1986) is needed. Jokipii and co-workers have achieved some success with a model in which changing geometry of the field and its influence on the drifts of the particles is the dominant mechanism of cosmic ray modulation. Since the role of changing three dimensional geometry of the interplanetary space is largely speculative and will remain so until insitu observations of such parameters as the velocity of the solar wind, the spectrum of magnetic fluctuations, and cosmic ray fluxes can be extended well above the ecliptic and obtained with the three dimensional models of cosmic ray propagation in the heliosphere. It seems prudent to try to extract some knowledge about these parameters from indirect methods.

3.2 DETERMINATION OF HELIOMAGNETIC LATITUDINAL GRADIENTS

In accordance with present models of IMF (Schulz, 1973; Saito, 1975; Svalgaard and Wilcox, 1976; Smith et.al., 1978) a warped current sheet is assumed to separate the two hemispheres of opposite magnetic polarities. The field is assumed to point outward (positive) everywhere above the current sheet and inward (Negative) below the current sheet for the post 1969 epoch. The reversed field is assumed for the pre-1969 epoch. As the Sun rotates every 27 days the Earth will be located above the current sheet (i.e. the North) for a certain period(s) and below (in the South) during the rest of the period. This passage of the neutral sheet or heliospheric current sheet at the location of the Earth is interpreted as the sector boundary crossing. The Earth sees a reversal of the magnetic polarity (positive to negative or negative to positive) on each crossing of the current sheet.

It is now well established that the heliospheric current sheet is not coincident with the heliographic equator but, in general, is tilted. This leads to a large-scale warp in the current sheet structure as it propagates away from the Sun. It has been further demonstrated that there is a solar cycle variation in the angle of tilt and, therefore, in the latitudinal extent of the current sheet warp [Svalgaard and Wilcox, 1974; Thomas and Smith, 1981]. The sector pattern and the heliospheric current sheet changes with solar cycle and the direct evidence for the solar cycle variation in the configuration of the current sheet was noted by Bruno et.al. (1982). They found that in 1976 the sheet was nearly parallel to the solar equator and symmetrically warped so that an observer near the equator would see four sectors and a similar pattern was observed in 1964-65 one cycle earlier. The latitudinal extent of the current sheet was found to be on average 8^{o} and the maximum extent 15^{o}. In 1975 the inclination of the dipole was $\sim 10^{o}$ and the current sheet was warped asymmetrically at times. Zhao and Hundhausen (1981) inferred that in 1974 the Sun's magnetic field was predominantly inclined at $\sim 30^{o}$ with respect to the Sun's rotation axis. Thus these isolated studies taken together suggest that the inclination of the dipole axis with respect to the solar rotation axis decreased with decreasing solar activity, and the two axes were nearly aligned near solar minimum (Burlaga, 1983). The theoretical calculations of Hoeksema et.al. (1983) do suggest that the effective current sheet tilt becomes very large near solar maximum. Furthermore a recent study using the result of Hoeksema et.al.(1983) indicates that the simple picture of a single highly inclined current sheet at this time is capable of organizing the observed cosmic ray intensities quite well (Smith and Thomas, 1986).

The available in-situ measurements are limited (in latitude) by the fact that most spacecraft orbits lie in or near the ecliptic plane. This limitation however, is less severe than it seems, for the Sun's rotation axis is tilted 7.5° with respect to the normal to the ecliptic, allowing us to sample a solar latitude range of atleast 15°. Whenever the Sun's magnetic dipole is inclined with respect to the rotation axis the available range of magnetic latitudes may be even larger. For example, Zhao and Hundhausen (1981) examined measurements of the bulk speed and density of solar wind obtained at 1 A.U. in 1974, and they found changes which could be interpreted as latitudinal variations with respect to a magnetic dipole axis inclined $30^{\circ} \pm 10^{\circ}$ from the rotation axis. Specifically, they found that the speed was smallest near the magnetic equatiorial plane (which would correspond to the heliospheric current sheet) and increased with latitude. The Sun is uniformly quiet perhpas during a year or so around the sunspot minimum period. Around this period of solar minimum the solar magnetic field takes on the form of a tilted dipole, the corona is dominated by coronal holes which extends nearly to the equator from the magnetic poles, and the heliosphere takes on the form of a simple tilted dipole with opposite magnetic polarity in opposite hemispheres and a somewhat corrugated current sheet at the magnetic equator (Cf Hundhausen, 1977). Such epochs are also one of the great stability of the corona and the interplanetary medium suggest that the heliospheric plasma, magnetic field and cosmic rays are in an steady state (approximately). The rotation of the Sun and the heliosphere then provides the means for an Earth-based detector to sample heliomagnetic latitudes upto $\pm$ 30^{o} every rotation rather than $\pm$ 7^{o} every year (Newkirk and Lockwood, 1981).

It is now well known that the inclination of the current sheet does inncrease as solar maximum approaches, [Thomas et.al, 1986]. A systematic change of the orientation of the solar dipole axis during a solar activity cycle was also proposed by Saito (1975). It has been suggested that the bending of the current sheet arises as a result of North-South asymmetry in solar activity (Mori and Saito, 1979). Also, it is now generally accepted that it is the rotation of the tilted dipole and the current sheet with respect to the rotation axis of the Sun which causes the alternating polarity of the radial component of the IMF which is observed in the interplanetary space (Smith et.al., 1978). Thus, for a simple tilted dipole the Earth is located above the current sheet for about 27/2 days and below it for about 27/2 days. During the period when the solar dipole moment is directed northward, the radial component of the IMF is directed outward (awav) when the Earth is located above the current sheet and inward (toward) when the Earth is located below the current sheet (Hakamada and Akasafu, 1981). This concept of wobbling solar dipole and of the current sheet has been confirmed by Thomas and Smith (1980) and Smith and Thomas (1986). So from the above discussion it can be inferred that the Earth's distance with respect to solar magnetic equatorial plane and thus to current sheet varies systematically as the Sun rotates every 27 days.

In the present Chapter we have used the neutron monitor data from Thule (cut-off rigidity 0.0 GV),Deep River (cut-off rigidity 1.02 GV),Rome (cut-off rigidity 6.32 GV) and Huancayo (cut-off rigidity 13.45 GV), well distributed in latitudes. Chree epoch method has been applied, using the sector boundary crossing data (Svalgaard, 1976; Wilcox and Scherrer, Private communication) as the epoch day, to study the latitudinal gradients of cosmic rays in the heliosphere. Since the Sun is almost quiet around sunspot minimum period, we first applied the above method to study the variation of cosmic ray intensity near the heliospheric current sheet (both above and below) during the two solar activity minimum period (1964-65) and (1975-76). The interplanetary field lines were directed inward above the current sheet and outward below it during (1964-65), while the field lines were outward above the current sheet and inward below it during the period (1975-76). Then the periods of study (1964-76) have been divided into two groups 1964-68 and 1969-76, when the IMF in the Northern and Southern hemispheres have reverse configuration. This study has also been made, separately, for the periods when the Northern magnetic pole of the Sun was negative (1964-68) and positive 1972-76 and also during the period when the polarity reversal took place (1969-71). The periods of rising, maximum and declining solar activity i.e. 1966-68, 1969-70 and 1971-73 were also studied separately. In this way a systematic study has been made to study the density gradient of cosmic rays, in the heliosphere, with particular emphasis of the effect near the heliospheric current sheet by using a relatively simpler method, during different epochs of solar cycle, as discussed above. Due to non availability of the direct data by spacecrafts from higher latitudes (since most spacecraft orbits lie in or near the ecliptic plane) this simple approach of determining the latitudinal gradient of cosmic rays in the heliosphere seems quite informative. The latitudinal distribution of cosmic ray in the heliosphere has been of considerable interest and discussion in the last few years, both from theoretical and observational points of view (as discussed in later section). The implications of our results are discussed.

3.3 LATITUDE GRADIENT OF COSMIC RAY INTENSITY IN THE HELIOSPHERE-THEORETICAL ASPECT AND EXPERIMENTAL RESULTS

Since the theoretical models of cosmic ray propagation including drifts in the large-scale field predict on unabiguous latitudinal gradient of particle flux with respect to the heliospheric current sheet, data on this dependence should provide an independent means of establishing the importance of drifts. However, direct determinations of this quantity by means of satellites spaced in latitude are often confounded by the small range in latitude covered and the inevitable confusion of latitudinal, radial and temporal differences in cosmic ray flux, Indirect determinations, in which the inclination of the rotating current sheet provides the means of exploring conditions over a range of latitudes, generally cover a wider range in latitude at the same radial distance but are still subject to the presence of unknown temporal and latitudinal variations. There are two indirect methods to detect the perpendicular cosmic ray density gradients using cosmic ray detectors on the Earth. One is to use the Earth's excursion of $\pm$ 7.25 in heliolatitude during the year, which can give rise to an annual wave in cosmic ray intensity. In this method annual and semi-annual components are evaluated by means of Fourier analysis (Antonucci et.al. 1978). These authors have found that the cosmic ray gradient, perpendicular to the solar equatorial plane, regularly changes its direction at the solar activity maximum, displaying a 22 year periodicity.

The second method of detecting perpendicular cosmic ray density gradient at the Earth makes use of contribution of drift term $\vec{B} \times \vec{\nabla} N_p$ to the solar diurnal cosmic ray variation ($\vec{B}$ is the IMF vector, $\vec{\nabla} N_p$ is the cosmic ray density gradient perpendicular to the ecliptic plane). This method has been described by Swinson (1970) and Hashim and Bercovitch (1972). Their results are consistent with a southward perpendicular gradient during 1967 and 1968. This method was further used by Kananen et.al (1981) and Swinson and Kananen (1982) for the analysis of longer period. They found the results which point to a cosmic ray density gradient, perpendicular to the ecliptic plane, pointing southward from 1965 to 1969 and changing to northward pointing gradient after the reversal of Sun's polar magnetic field in 1969-71, extended upto 1975. In a later extension of the above work swinson (1983) and Swinson et.al. (1986), using the underground cosmic ray telescope data from 1975 to 1982, found no sustained perpendicular gradient (either northward or southward) throughout this period of time, though solar polar field reversal took place in 1980-81 (Howard and Labonte, 1981). In a similar analysis on geomagnetically quiet days, Badruddin et.al. (1985) have concluded that the North-South asymmetry in solar activity seems to be influential in determining the latitude gradient of cosmic ray flux.

Subramanian and Sarabhai (1967) and Lietti and Quenby (1968) postulated the existence of a cosmic ray density gradient perpendicular to the ecliptic plane for the explaination of the observed solar semi-diurnal cosmic ray variation. This proposed gradient required a minimum density of cosmic rays in the ecliptic plane, with the density increasing with distance both above and below the plane. Later Subramanian (1971) found results indicating a cosmic ray density increasing with distance below the ecliptic plane and decreasing above it during the period 1962-1965. Kane (1968) demonstrated the variability of the perpendicular gradient during different periods between 1960 and 1967. His data indicate that for 1965-66 any perpendicular gradient existing was small, which is consistent with little or no perpendicular gradient during that period. Kane's data, however, do indicate a southward perpendicular gradient for 1967 and 1968.

Although it has long been recognised that there is considerable azimuthal and latitudinal variation in the heliosphere, modulation models have until recently ignored this structure and considered mainly spherically symmetric cases. However, as shown by Fisk (1976), Newkirk and Fisk (1985) and Newkirk et.al.(1986), three dimensional effects (off-ecliptic variations) can substantially affect near ecliptic measurements like radial gradients or spatial anisotropies. Recently attempts have been made to incorporate these three dimensional effects into the modulation theory of cosmic rays. The impetus of this, is the direct observation by Pioneer space probes of the interplanetary magnetic field structure (C_f Smith and Wolfe, 1979). The importance of the above large scale structure of the field lines lies in the transport of cosmic rays across the field lines due to curvature drifts. Even in the absence of any latitude dependence of parallel and perpendicular diffusion coefficients, the radial diffusion coefficient will vary with latitude as the Archemedian spiral angle will vary with latitude. But the parallel and perpendicular diffusion coefficients will vary due to scattering by waves in the solar wind plasma varying with the heliographic latitude. Hence it is quite clear that any theory of transport of cosmic rays in the interplanetary space has to incorporate three dimensional effects (Ramadurai, 1981).

The variation in the modulation of cosmic rays with latitude in the models of Fisk (1976), Newkirk and Fisk (1985) and Newkirk et.al. (1986) is caused solely by the expected latitude variations in the direction and the amplitude of the IMF. Levy (1978) in his attempt to explain the observed semi-annual variation in the galactic cosmic ray flux observed at Earth, pointed out that the general dipole - like symmetry of the IMF produces a heliospheric latitude variation in the density of the modulated cosmic rays.

A simple calculation demonstrates that for particles in the GeV range, their drift velocity normal to the field due to its gradient and curvature may become significant or even dominant in the outer solar system. The current interest in the ability of the solar wind to modulate the cosmic ray intensity is focussed on the evaluation of the importance of the particle drift motion caused by gradients in and curvature of IMF in exchanging cosmic ray particles between solar equatorial and solar polar latitudes (Jokipii et.al., 1977; Jokipii and Levy 1977; Jokipii and Kopriva, 1979; Isenberg and Jokipii, 1978, 1979; Jokipii and Davilla, 1981; Kota, 1979; Moraal et.al., 1979; Kota and Jokipii, 1982, 1983). Jokipii and Kopriva (1979), on the basis of a two dimensional model, in which drift plays a dominant role, predicted a sharp increase in cosmic ray density away from the solar magnetic equator in 1969-81 and a sharp decrease during 1958-68 and 1981-92. In other words they have provided numerical solutions of modulation equations including drift motion which yield a positive gradient towards higher heliolatitudes if the northern solar field is predominantly outward while the gradient is negative if the general solar field is reversed. These have emphasized the importance of drifts and revealed the existence of a new type of modulation based on the balance between drift and energy loss in which diffusion plays a negligible role. Jokipii and Thomas (1981) and Smith and Thomas (1986) have suggested that the changes in the waviness of the interplanetary current sheet can be an important effect in producing solar modulation of galactic cosmic rays and any process which increased the waviness of the current sheet would have a similar effect. On the basis of a three dimensional model for solar modulation including drifts, Moraal et.al. (1979) have shown that the particles seen at the Earth cross the boundary of the modulation cavity at very different heliolatitudes, depending on the sign of IMF. However, off-ecliptic gradient is always positive towards the poles. Moraal et.al. (1979) also claim that in the post - 1970 period, the equatorial intensity should be higher due to reduced latitudinal gradient, a prediction supported by stratospheric monitoring by Charkhchyan and Stozhkov (1981). Potgieter and Moraal (1983) presented further numerical solutions of the two-dimensional steady state transport equation in the three-dimensional axisymmetric heliosphere and found that the intensity at the poles is greater than at the equator for both pre - 1970 and post - 1970 but the latitudinal gradients are larger for the pre - 1970 period. Erdos and Kota (1981) have made calculations using a model based upon calculating energy losses along regular particle trajectories in an IMF model incorporating a wavy neutral sheet. They calculate the density distribution of the 50 GV cosmic rays for the two periods before and after the Sun's polar field reversal and find that the latitudinal gradient changes sign with polarity reversal on the Sun; cosmic ray intensity increases towards poles for the 1969-80 magnetic configuration, while it decreases away from the solar equator for opposite magnetic configuration. These results closely resemble those obtained by Jokipii and Kopriva (1979) at lower energies.

The geometry of the wavy current sheet is an important factor in propagation models including particle drifts. Newkirk and Lockwood (1981), Newkirk and Fisk (1985) and Newkirk et.al. (1986) used heliomagnetic latitude and angular distance from the current sheet to organise their observations. In their studies, ground-based synoptic observations of the K-corona are used to determine the shape of the current sheet at the Corona. This synoptic coronal information was then used in combination with solar wind velocity data to infer the position of the current sheet in latitude and longitude at 1 AU.

Newkirk and Fisk (1985) reported on a study of the latitudinal profile of 5-GeV cosmic ray at 1 AU during the last solar cycle in which they assumed that the coronal current sheet is located on the mid point of the 'band of streamers' identified in the synoptic K Corona-meter observations at a radius of 1.5 R_s. Their profiles were expressed as a function of the displacement in ecliptic latitude between the Earth and the interplanetary current sheet swept out radially from the corona with the solar wind speed observed at 1 AU. Their principal conclusions were that

1. the flux decreases at a rate of 2% /AU away from the current sheet during years of low solar activity,
2. the gradient does not appear to be sensitive to the polarity of the large-scale heliospheric field.

However, Newkirk and Lockwood (1981), employing a latitude defined by K-Coronameter data (magnetic latitude) and using the cosmic ray data of a neutron monitor, find that the cosmic ray gradient does not change sign but that the intensity is always higher at the Equator. In other words they found a negative correlation between cosmic ray intensity and the Earth's heliomagnetic latitude (i.e. the distance from the current sheet) for both halves of the 22 year cycle. They used the Mt-Washington neutron monitor data, for the two selected minimum periods, September - October 1965 and May - June 1975. This result is seemingly in contradiction to the expectations of the drift model which for a flat neutral sheet, at least, predicts a fairly sharp increase of cosmic ray intensity away from the current sheet for 1975 (Jokipii and Kopriva, 1979). Further, the results of Newkirk and Lockwood (1981) point to a higher gradient for 1975 than for the 1964 period. Kota and Jokipii (1982, 1983) in a subsequent simulation extended the full two-dimensional calculations, and including diffusion, to a three-dimensional computational code which permits a wavy current sheet to be incorporated. These calculations present the first study of the steady state modulation of cosmic rays by solar wind in which all major transport effects - convection with solar wind, anisotropic diffusion, particle drifts and energy loss - are included in a fully three dimensional model. In general the results support their earlier, less comprehensive calculations which included drifts and in addition, they show that including diffusion as well as drifts produces qualitatively new behaviour near the wavy current sheet. In particular they found that the intensity decreases away from the current sheet for both signs of solar magnetic field, in contrast with the earlier results which do not include diffusion. This is at least in qualitative agreement with the results obtained by Newkirk and Lockwood (1981). But there is an apparent discrepancy in magnitudes since the calculations of Kota and Jokipii (1982, 1983) give a steeper regression for the pre - 1969 period then they do for the post - 1969 period. Newkirk and Lockwood (1981), on the other hand, observed a steeper regression for 1975 then 1965 period.

Studying the 22-year variation of the solar diurnal variation, based on the diffusion - convection equation which has a self consistent expression concerning the electric field $\vec{E} = -\vec{V} \times \vec{B}$, Nagashima and Munakata (1983) have noted that in the post-1969/70 period, the near Earth density of the cosmic rays is higher than that in the pre-1969/70 period and the latitudinal density gradient is considerably higher.

Use of the conventional guiding centre theory for drift has demonstrated that the magnitude of the latitudinal gradient in cosmic ray intensity can be profoundly altered depending on the phase of the cycle of the solar magnetic field. Using numerical simulation techniques, drift motion and perpendicular diffusion is studied by Moussas et.al. (1982) and it was suggested that the perpendicular diffusion may be an important process for the propagation in the IMF. The perpendicular diffusion effects on the gradient of cosmic rays donot depend on the sign of the solar field and hence the enhanced importance suggested makes any off-ecliptic gradient less sensitive to the 22-year cycle.

It is only recently that it has been possible to directly detect cosmic ray gradients that vary in heliolatitudes. This has been achieved by simultaneous use of multiple spacecrafts (McKibben et.al. 1979; Roeof et.al., 1981); these measurements are for a limited period of time and at relatively low energies.

3.4 RESULTS AND DISCUSSION

Figure 3.1 shows the result of a superposed epoch analysis (with reference to IMF sector boundaries or heliospheric current sheet crossings) of nucleonic intensity data from four neutron monitors, well distributed in latitude from the pole to the Equator. The two periods selected for the analysis are the minimum activity period before and after the reversal of the solar magnetic field around the solar maximum period in solar cycle 20. It is assumed that the current sheet separates positive (negative) fields in the Northern Hemisphere from negative (positive) fields in the Southern Hemisphere and generally the fields above, or North, of the current sheet are inward or negative and fields below, or South of the current sheet are outward or positive in the period 1964-65. But the fields are directed in reverse directions above and below the current sheet in the period 1975-76. Thus in 1964-65 in a positive sector the observer is thought to be below the current sheet and in a negative sector it is above the current sheet and passes through the current sheet on the day of the sector boundary crossing. The situation is reversed in the period 1975-76. It may be mentioned here that we have considered, for our analysis, the days when there is one particular polarity at least for 5 days before the sector boundary crossing and the reverse polarity, also at least for 5 days after the sector crossing.

We can see from Fig. 3.1 that the cosmic ray intensity

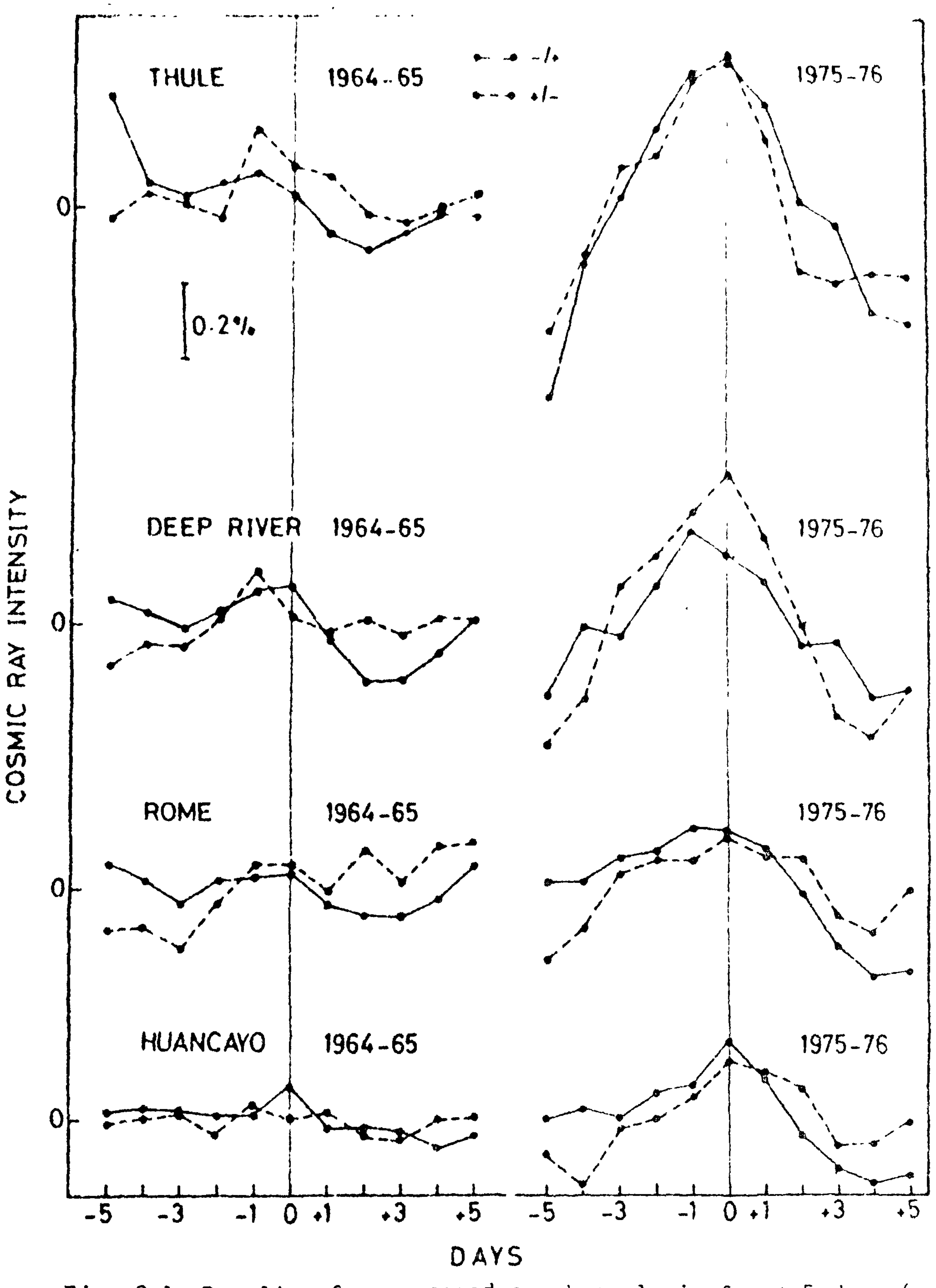


Fig. 3.1 Results of superposed epoch analysis for ± 5 days (zero day corresponds to the IMF sector boundary corssings) for the galactic cosmic ray intensity for the periods 1964-65.

decreases for a few days - both after -/+ and +/- sector corssing - and then it starts recovering towards maximum intensity which is observed on the day of sector boundary crossing. In other words it can be said that the cosmic ray density is higher near the current sheet and it decreases as the heliomagnetic latitude increases. This is true for both the periods considered, i.e. for 1964-65 and 1975-76. It can also be seen from the figure that the latitudinal gradient is nearly symmetrical both above and below the heliomagnetic equator during these periods of minimum activity.

Another result that can be inferred from these figures is that the negative latitudinal gradient is much steeper during the period 1975-76 then 1964-65. Newkirk and Lockwood (1981), using the data from a mid-latitude station for 2 months duration during each period, have also found similar results. Potgieter et.al. (1980) found a significant difference between the 1965 solar minimum response function of sea level neutron monitors and those for the period of solar minimum during 1976. The difference suggests that the cosmic ray spectrum was harder during 1965 than in 1976. This difference in cosmic ray spectra at subsequent solar minimum is, as suggested by Potgieter et.al., (1980), related to the polarity of the interplanetary magnetic field.

Models of cosmic ray propagation including drifts in a heliosphere with a planar current sheet inclined to the solar equator predict that such negative gradients in flux should be present (Kota and Jokipii, 1982). Indeed the gradient observed duri g the 1973-1977 minimum in solar activity can be reproduced by a model with reasonable choices of the parallel and perpendicular diffusion coefficients. [Such a comparison between theory and observation takes account of the fact that the observed profile of cosmic ray flux for any extended period is an ensemble of many different profiles accumulated with a wide variety of inclinations of t.e current sheet (Jokipii and Kota, 1986). The ensemble of intrinsic profiles is also distorted by the dependence of the overall level of cosmic ray flux upon inclination (Jokipii and Thomas, 1981, Smith and Thomas, 1986) and the limited range of latitudinal displacement from the current sheet accessible with a given inclination]. This agreement demonstrates only that the drifts dominated models may apply to the real heliosphere. Since drift velocity is a strong function of particle rigidity, one might hope that the rigidity dependence of the latitudinal profile might well discriminate between these two vastly different models of cosmic ray propagation.

Although the drift flux in the formulation which consists of contribution from curvature and gradient drift was included in the original formulations of modulation theory (Axford, 1965, Parker, 1965), the observed sector structure of the IMF was thought to minimise its importance. With the recognition of the importance of the off-ecliptic effects and the disappearance of sector structure (Smith et.al., 1978) the necessity of taking the drift term into account was felt. In a series of recent papers (Jokipii et.al. 1977; Jokipii and Kopriva, 1979; Jokipii and Davilla, 1981; Kota, 1979), the importance of particle drifts in cosmic ray transport in interplanetary space has been reemphasized. They stress that the drifts dominate the motions of substantial portion of galactic cosmic ray particles. However, doubts exist as to whether the drift formulation is correct for the condition of large scale magnetic turbulence found in the solar wind (Lee and Fisk, 1981). Evidence has been cited both supporting (Antonucci et.al. 1978; Levy, 1978; Shea and Smart 1981; McKibben et.al., 1979) and denying (Evenson et.al. 1979; Cooper and Simpson, 1979) the dominance of drifts. Thomas and Gall (1982) studied the propagation of cosmic rays reaching the Earth by simulation of particle trajectories in the models of heliospheric magnetic fields, including the effects of CIRs. They concluded that strong field gradient associated with CIRs greatly perturb the drift pattern anticipated for simple Parkerian fields and thus the expected streaming of cosmic rays from over the poles or along the current sheet during the consecutive cycle no longer holds. However, Moussas et.al. (1982) have shown that gradient and curvature drifts can be present even in a highly perturbed field and thus they can have some influence on cosmic ray modulation.

Newkirk and Lockwood (1981), Newkirk and Fisk (1985) and Newkirk et.al. (1986), by employing a latitude defined by K-Corona meter data (heliomagnetic latitude), found that the cosmic ray gradient does not change but the intensity is always higher at the equator. This result is contrary to the two dimensional calculation of Jokipii and co-workers which included drift but neglected diffusion. Recently, Kota and Jokipii (1982, 1983) presented the results using a full 3-dimensional model which incorporates all known important effects on particle transport, i.e. particle drifts, convection with solar wind, energy loss and anisotropic diffusion. They find substantial effects due to the warp of the current sheet. Among other things they showed that the intensity may decrease away from the current sheet for both signs of magnetic field, in contrast with inferences from earlier more approximate calculations. These earlier calculations could not explain the observations of Newkirk and Lockwood (1981) in which intensity decreased away from the current sheet for both signs of IMF. However, from 3-dimensional computational code which permits a wavy current sheet to be incorporated, the results are shown (Jokipii and Kota, 1986) to be in general agreement to the observations of Newkirk and Lockwood (1981), Newkirk and Fisk (1985) and Newkirk et.al. (1986), but these calculations of Kota and Jokipii (1982, 83) predict a much steeper latitudinal gradient during the period before the reversal of the magnetic field in the solar cycle 20. However, our analysis shows that the latitudinal gradient is much steeper during 1975-1976 which is the period after the reversal of the polarity of the magnetic field, as compared to the period 1964-65 when there is much smaller gradient in latitude. Maussas et.al. (1982)

have studied the energetic particle propagation in IMF by the computer simulation of its motion in order to calculate perpendicular diffusion coefficient and average drift velocity in an ensemble of particles. They neglected the electric field contribution ($\vec{E} = -\vec{V} \times \vec{B}$, $\vec{V}$ is the solar wind velocity). Their results show that the gradient and curvature drift can be present even in highly perturbed fields and thus can have some influence in cosmic ray modulation. They also found that small scale random fluctuations in the field gradient and curvature can be at least of some importance in causing the perpendicular diffusion. While studying, theoretically, the 22-year variation of the solar diurnal anisotropy, based on the diffusion convection equation which has a self-consistent expression concerning the electric field $\vec{E} = -\vec{V} \times \vec{B}$, Nagashima and Munakata (1983) have noted that in the post - 1969/70 period, near-Earth density of cosmic rays is higher than that in the pre-1969/70 period and the latitudinal density gradient is considerably larger.

From the above discussion we do not intend to discuss the authenticity of the drift model - however, we do speculate that, if drifts are important in solar modulation, the discrepency in latitudinal gradient of cosmic rays predicted by 3-dimensional drift models which include diffusion, and our observational results can be removed by including the latitude-dependent solar wind velocity, at least during periods of solar minimum. Potgieter and Moraal (1983), by including the latitude-dependent solar wind velocity in the drift model of cosmic ray transport, have found that such a dependence has an effect on modulation. Sime and Rickett (1978) have found that the source regions of the high speed solar wind are not symmetric about the rotation axis but were centred more than 30^{o} from the rotation axis during 1973-75. From these results it can be inferred that a high speed solar wind tends to originate from the regions outside the bright belt of the white light corona. This coronal bright belt may be a manifestation of the magnetic equator (Pneuman, 1976). Thus it is reasonable to infer that the latitudinal dependence of the solar wind velocity is actually the magnetic latitude dependence (C_f Hakamada and Akasofu, 1981). These authors attempted to reproduce the 27-day variation of the solar wind observed near Earth between 1966 and 1979 by assuming a tilted magnetic dipole and a solar wind speed increasing with distance from the equator. Zhao and Hundhausen (1981) also found that the speed was smallest near the magnetic equatorial plane (which would correspond to the heliosphere current sheet) and increased with latitude. However, the latitudinal gradient in velocity inferred by Hakamada and Akasofu (1981) was twice as large as derived by Zhao and Hundhausen (1981).

In Fig. 3.2 we have shown the results of Chree epoch analysis with sector boundary passage date as the key-day.. In this figure the total period of solar cycle 20 is divided into two parts according to the field polarity above and below the current sheet; the period 1964-68 when the field is assumed to point inward above the current sheet and outward below it, and the period 1969-76, when the reverse field is assumed, i.e.

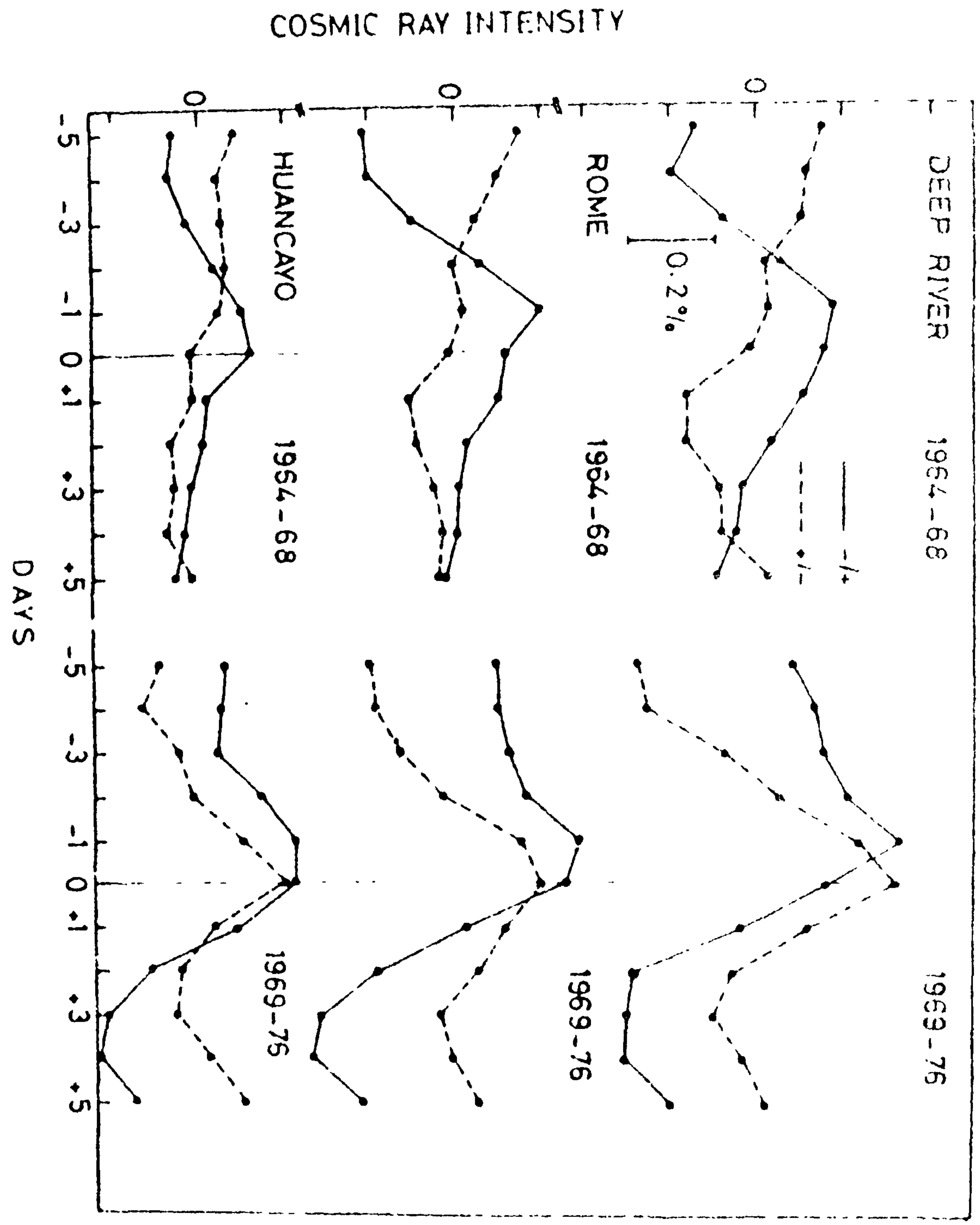


Fig. 3.2 Superposed epoch analysis results of cosmic ray intensity with epoch of IMF sector boundary crossings for the periods 1964-68 and 1969-76.

the field pointing outward above the current sheet and inward below it. This assumption is similar to that Erdos and Kota (1980). The negative latitude gradient is evident in both the periods. During the period 1964-68, the Earth is above the sheet (in the North) on the negative polarity days. After sector boundary corssing the Earth finds itself below the current sheet (in the south).

Solar activity was high during the period 1966-68. Moreover, the North-South asymmetry in the solar activity is also large (Yadav et.al. 1983; Badruddin et.al. 1983) i.e..the solar activity in the Northern Hemisphere was much larger as compared to the Southern Hemisphere. From the figure it can be seen that cosmic ray density is higher when the Earth is located in the positive polarity region (below the current sheet) then when it is in the negative polarity region (above the current sheet). Further the density is higher in the North of the current sheet.

The Chree analysis result for 1969-76 shown in Fig.3.2 reveals the decrease in cosmic ray intensity when an observer moves towards higher heliomagnetic latitude. This decrease in cosmic ray intensity is much higher when the observer is moving in the positive sector (i.e. above the current sheet) than when it is moving below the current sheet. During this period the solar activity, as evidenced from solar flares was very high in 1969 and 1970 and moreover the activity was much higher in the Northern Hemisphere than in the Southern Hemisphere. However, this activity was relatively lower during the period 1971-76 and also there was no appreciable asymmetry (on average) in the solar activity, although there was a slightly higher negative asymmetry in 1974.

In Fig. 3.3 we have divided the whole period of solar cycle 20 into three different periods: (1964-68) - (1969-71) and (1972-76). In (1964-68), the solar activity was increasing and the coronal holes were shrinking in size. The period 1969-71 is the period of reversal of the polar magnetic field of the Sun. During this period the solar activity was very high and the coronal holes were almost absent. In the period 1972-76, the solar activity was relatively low and high speed streams were prominent as the polar coronal holes were growing in size.

The analysis of neutron monitor data shows the negative gradient with respect to the current sheet during 1969-71. Also the higher density is observed when the Earth is in the negative sector (below the current sheet) than when it is in the positive sector (above the current sheet). Further, decrease in cosmic ray intensity seems higher when it moves above the current sheet than when it is moving away below the current sheet. During this period the solar activity was very high and also the North-South asymmetry was quite large.

In the results shown for 1972-76, the difference in cosmic ray density gradient, when the Earth moves above the current sheet and when it moves away below the current sheet, is considerably reduced. In this period the over all North-

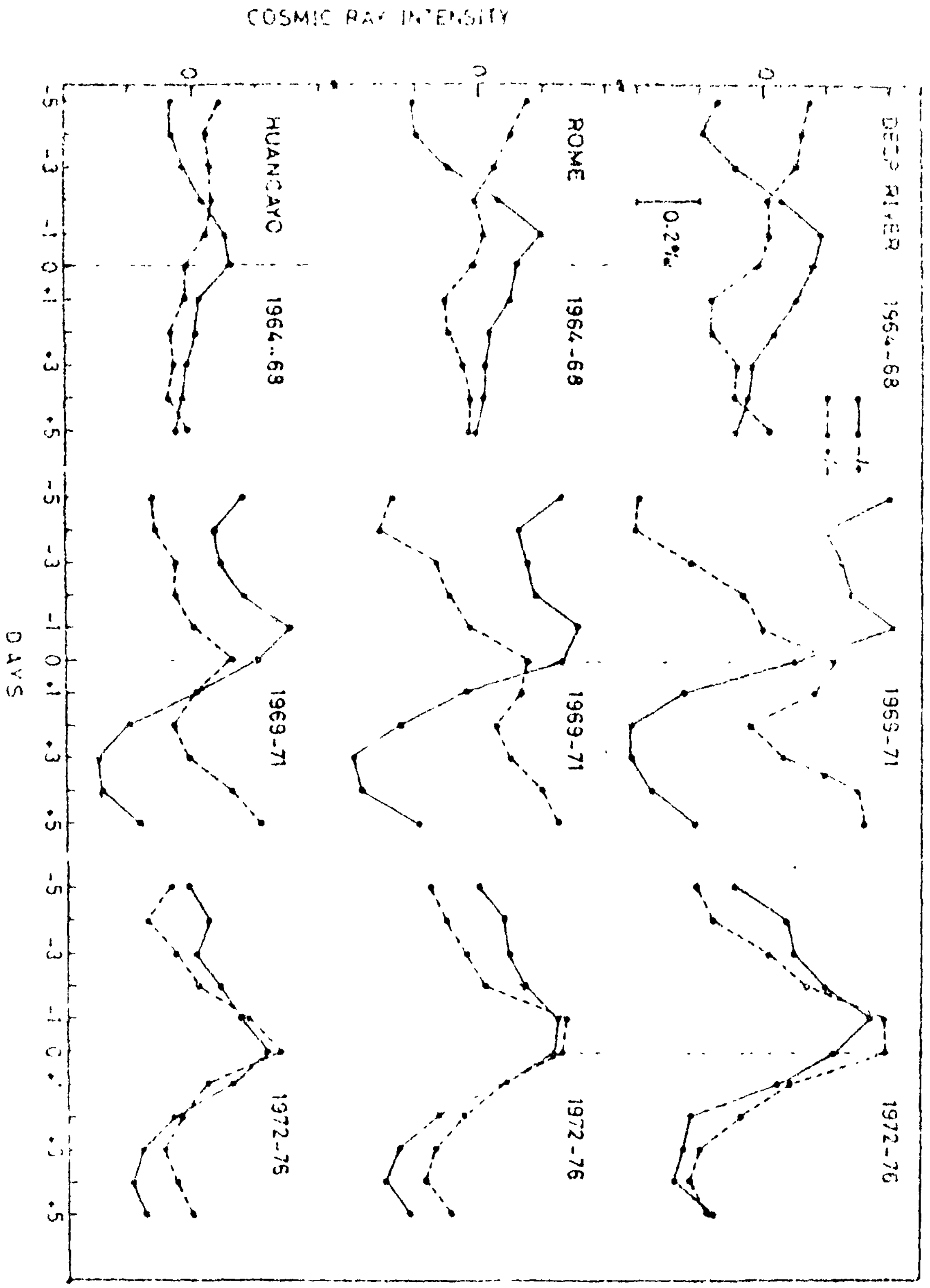


Fig. 3.3 Superposed epoch analysis results of cosmic ray intensity with epoch of IMF sector boundary crossing for the periods 1964-68, 1969-71 and 1972-76.

South asymmetry in the solar activity was very small though there is slightly higher activity in 1974.

In Fig. 3.4 we have considered the ascending phase, maximum phase and descending phase of solar activity of solar cycle 20 excluding the minimum activity periods i.e. 1964-65 and 1975-76 to see the behaviour of cosmic ray density gradient. In 1966-68 period and 1969-70 period the difference of density gradient is much as it was in Fig. 3.3 while in the period 1971-73 the difference is reduced. In 1973, prior to the last solar minimum, long-lasting cosmic ray variations ('mini-solar cycle effects' not Forbush decreases) were observed (Smith and Thomas, 1986). With G. Newkirk they have carried out a preliminary analysis of the possible correlation of these cosmic ray variations with the latitudinal extent of the coronal disc inferred from K-coronameter data. Their results indicate that the cosmic ray decreases accompany excursions of the coronal disc/current sheet to higher latitudes.

However, the long-lived streams of high speed solar wind were prominent in these years (1972 - 1976). These fast solar winds flow from polar holes and extend equator ward, with slow winds occurring in a limited spatial band centered on the magnetic neutral line (Hundhausen, 1979). A correlation between cosmic ray intensity and the size of the polar coronal holes during the period 1965-1976 has been reported by Hundhausen et.al. (1980). They found that the coronal holes are influential in determining the 3-dimensional modulation of galactic cosmic

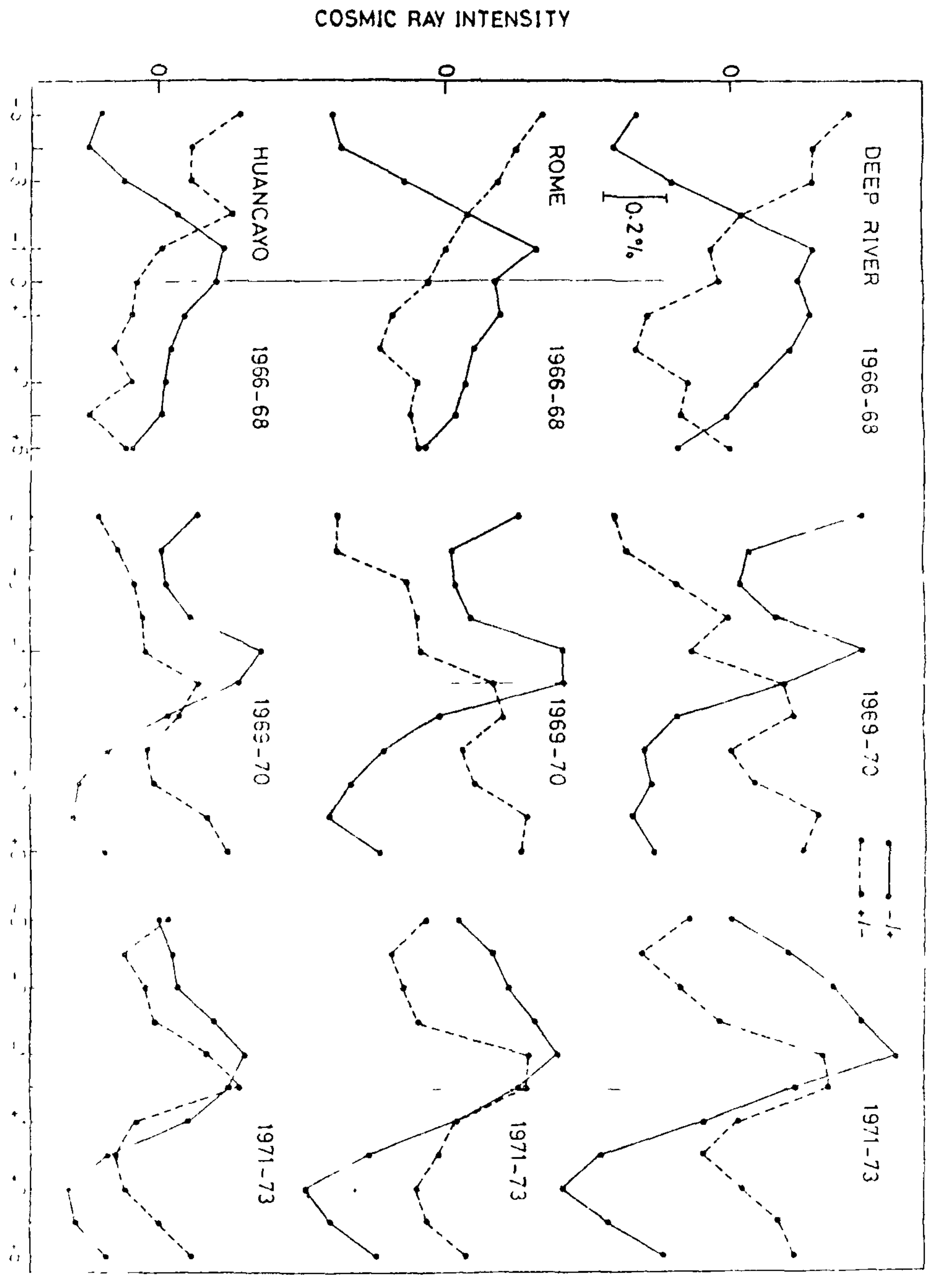


Fig. 3.4 Syperposed epoch analysis results of cosmic ray intensity with epoch of IMF sector boundary corssings for the periods 1966-68, 1969-70 and 1971-73.

rays in the solar system. Later on the basis of coronal hole geometry Ahluwalia and Riker (1981) have suggested that after 1971 electromagnetic conditions in solar corona make it easier for off-ecliptic cosmic rays to be transported from high heliolatitudes to low heliolatitude location in the solar corona. During solar cycle 20, polar coronal holes shrink in size from 1965-67 during the ascending phase of the solar cycle and they almost disappeared in 1969 and 1970, which is the period of polar field reversal. However, they reappeared in 1971 and grew in size during descending phase of the cycle, and these polar coronal holes have their larger size during the sunspot minimum (Hundhausen et.al. 1980). The amplitude of the solar wind stream appears to be directly related to the size of the coronal holes (C_f Zirker, 1977). Small, low latitude coronal holes tend to be associated with relatively narrow streams (500-600 Km/sec) at the Earth while large coronal holes, even at mid latitude are more apt to be associated with relatively wide streams when speed at Earth sometimes exceeds 700 Km/Sec (Broussard et.al. 1978). It may be possible that the asymmetry in the size of northern and southern polar coronal holes has some influence on the differences in latitudinal gradient above and below the current sheet, especially during the descending and minimum phases of the solar activity cycle when the level of solar activity was not high and the North-South asymmetry was quite small.

3.5 CONCLUSION

We suggest that the results of our analysis can be explained as follows: as the Sun rotates the Earth's distance with respect to the current sheet varies. An observer on the Earth sees a decrease in cosmic ray intensity as it moves away from the current sheet. After a few days when it starts moving towards the current sheet, the intensity of the cosmic ray particles starts increasing and the maximum cosmic ray intensity is observed near the current sheet. If the current sheet lies in the ecliptic plane, throughout the solar cycle, our results may be interpreted to indicate that the value of the density gradient pointing away from the solar equatorial plane is not symmetrical above and below it, at least during the periods of high solar activity and appreciable North-South asymmetry. Alternatively the current sheet might have been displaced from the ecliptic plane due to asymmetric activity in the Northern and Southern Hemispheres of the Sun. In such a situation the extent of the Earth's excursion in heliomagnetic latitude will be different above and below the current sheet. However, if the theoretical results showing the symmetric density gradient on either side of the equatorial plane are correct, then the second alternative seems a more plausible explanation.

CHAPTER IV

COSMIC RAY DIURNAL ANISOTROPY DURING INTERPLANETARY MAGNETIC CLOUDS

4.1 INTRODUCTION

'The daily variation' is defined as that portion of the total intensity variation with a frequency of $\frac{1}{24}$ h^{-1} or harmonics thereof. It includes the diurnal variation which is the repetitive portion of the daily variation over many solar rotations. The diurnal variation, in contrast to daily variation is not a true time variation in space, but rather arises because the observations of the cosmic radiation are made from the reference frame of the Earth. The diurnal variation represents a net drift of cosmic ray gas with respect to the reference frame of the Earth. The diurnal variation remains approximately fixed in spatial orientation and is produced by the corotation of the cosmic ray gas with the Sun.

Even though occasional attempts (Rao and Sarabhai, 1964) have been made by few workers to study the cosmic ray daily variation in its entirety without resorting to divide it into its harmonics, most of our information on cosmic ray daily variation has been derived through a study of diurnal and semi-diurnal components. A great body of experimental observations has been accumulated in the past concerning the daily variation of cosmic radiation. With the availability of data from neutron monitors for which the atmospheric effects are fairly well understood, it has been possible to examine the daily variation of cosmic radiation in a great detail. The improved statistics provided by the high counting rate neutron-monitors has further improved our knowledge of the daily variation.

The amplitude and the phase of the daily variation of the galactic cosmic ray intensity have been observed to change over various time scales, from day to day upto at least the 22-year solar activity cycle. (Pomerantz and Duggal, 1971, Forbush, 1973, Ananth et.al. 1974). Also on theoretical basis it is contemplated that, even during periods of quasi-stationary cosmic ray intensity, the diurnal effect could vary (Parker, 1964) in the extreme case in which the interplanetary magnetic field $\vec{B}$ is highly regular and steady $(\frac{\partial \vec{B}}{\partial t} = 0)$, the corotation of the cosmic ray gas with the Sun is prevented by the Lioville theorem (Stern, 1964); in fact as shown by Parker (1964) under such a condition, for a solar wind velocity $\vec{V}$, there results a cosmic ray gradient perpendicular to the ecliptic plane and oriented as $- \vec{V} \times \vec{B}$, which concels the streaming due to the corotation term. Similarly, in the other extreme case in which on the ecliptic plane the perpendicular diffusion is comparable with the diffusion parallel to the magnetic field lines (i.e. cosmic ray isotropic diffusion), the anisotropy tends to vanish (Pomerantz and Duggal, 1971, Rao, 1972), as it happens, for example, on the occasion of frequent polarity inversions in the interplanetary magnetic field in quasi-stationary condition (Iucci and Storini, 1973). The diurnal effect will be comparable with the one expected on the basis of corotation when at the Earth orbit $K_{||} << K_{\perp}$ and when somewhere along the magnetic lines of force crossing the Earth, inside or outside the Earth orbit, the cosmic-ray diffusion perpendicular to the field lines annuls the cosmic-ray gradient perpendicular to the ecliptic plane (Parker, 1964, Axford, 1965).

It is evident, however, that the amount of the anisotropy on each individual day will depend on the existing structure of the interplanetary magnetic field, on the cosmic ray density gradient and solar wind speed; the anisotropy may, therefore, reach values much higher than that provided by pure corotation; as it occurs for instance during some Forbush decreases in which the cosmic ray gas is far from the stationary condition.

More than four decades of studies of the diurnal variation of cosmic ray intensity, since the appearance of the first paper by Forbush (1937), have not completed our understanding of this aspect of the solar modulation of cosmic rays. New sets of data that are becoming available have thrown fresh light on an old problem. For example the possible influence of interplanetary magnetic field lines originating above coronal holes on the amplitude of the diurnal variation at neutron monitor energies has been pointed out by Roelof et.al. (1975). Extensive reviews by Pomerantz and Duggal (1971, 1974) and Rao (1972) and the references within these reviews provide a comprehensive survey of the subject.

Mc Cracken et.al. (1968), Forman (1970), and Forman and Gleeson (1975), following up on their studies of the anisotropies with low-energy solar flare particles, have pointed out that the diurnal anisotropy of galactic cosmic rays also arises from a superposition of convective and diffusive processes. Hashim et.al. (1972) have clearly demonstrated that the observed anisotropies can be satisfactorily explained by considering two components of the streaming galactic cosmic rays: (1) Convective streaming radially away from the Sun with solar wind speed and (2) diffusive streaming along the interplanetary magnetic field (IMF). This streaming is mostly towards the Sun. Hashim et.al. (1972) have further pointed out that the quiet time anisotropy can also be satisfactorily accounted for by such a description. Additional support for these ideas has also come from Mathews et.al. (1969), Ananth et.al. (1974) and Kane (1974, 1975).

With the assumption of an absence of both significant cosmic ray diffusion across the magnetic field and large values of cosmic ray gradients perpendicular to the ecliptic plane, the theories discussed above predict that the diffusive component of the anisotropy should be alligned along the mean ecliptic direction of the IMF. The occasions of significant departure from this allignment observed on a day to day basis have been attributed to the diffusion of cosmic rays normal to the mean IMF arising from enhanced magnetic field fluctuations and/or to the existence of perpendicular cosmic ray gradients (see also Owens, 1977,a,b). Gradients perpendicular to the ecliptic are observed for short periods in association with disturbed interplanetary conditions, [Duggal and Pomerantz, 1976].

If there is a transient disturbance in the interplanetary medium due to a shock wave associated with a solar flare, the balance between sunward diffusion and outwards convection by the solar wind of the galactic cosmic rays is upset; thus during a Forbush decrease the streaming of the cosmic ray gas might change considerably in both magnitude and direction. Cosmic ray streaming other than corotation with the Sun must occur as a result of departures of the solar wind cavity from spherical symmetry as pointed out by Parker (1964).

Recent developments indicate that anisotropies perpendicular to the ecliptic plane can provide a poweful diagnostic tool for understanding the mechanisms that produce the transient intensity variations. It has been established that anisotropy perpendicular to the ecliptic is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971, Mercer et al. 1971). Both the onset and the recovery phases of cosmic ray storms are often characterised by several types of transient phenomena. The most prominent superimposed modulations that occur during Forbush decreases (FD) are (1) enhanced diurnal variations (Lockwood, 1971; Pomerantz and Duggal, 1971) and (2) north-south anisotropies (Duggal and Pomerantz, 1976).

To explain the observed solar semi-diurnal cosmic ray variation, Subramanian and Sarabhai (1967) and Lietti and Quenby (1968) proposed the existence of a cosmic ray density gradient perpendicular to the ecliptic plane. The proposed gradient required a minimum density of cosmic rays in the ecliptic plane for the density increasing with distance both above and below the plane. A cosmic ray density gradient $\vec{\nabla} U$ in the presence of the interplanetary magnetic field (IMF) $\vec{B}$ causes a particle drift proportional to $\vec{B} \times \vec{\nabla} U$. If $\vec{B}$ is considered to lie in the ecliptic plane, the N-S component of $\vec{\nabla} U$ produces a flow in the ecliptic plane perpendicular to $\vec{B}$ whose sense depends on the sense of $\vec{B}$ (e.g. for $\vec{B}$ pointing away from the sun (positive) at an angle of 45° to the Sun-Earth line a south pointing gradient produces a flow from the direction 45° E of the Sun-Earth lines). This will be observed as a field correlated vector addition to the usual azimuthal streaming. The effect may be detected by separating the diurnal variation vectors into groups corresponding to positive and negative fields (Hashim and Bercovitch, 1972, Swinson, 1970).

It has been pointed out by Thambyapillai and Elliot (1953) that the solar diurnal variation of cosmic rays shows a 22-year variation depending on the solar activity. Since then, the existence of this phenomenan has been confirmed by many researchers (e.g. Forbush 1967, 1973; Duggal and Pomerantz, 1975; Mori et.al. 1981; and references therein). On the other hand, by the discovery of the polarity reversal of the helio-magnetic field every maximum solar activity period (Babcock, 1959, 61; Howard 1974) together with the development of the cosmic ray diffusion - convection theory (Parker, 1958, 1965; Gleeson and Axford, 1967), it became clear that the cosmic ray density in space shows a polarity state dependence due to the drift effect in the ordered magnetic field as pointed out by Jokipii et.al. (1977).

Recently, Munakata and Nagaslima (1984, 1986) have theoretically derived the first three order anisotropies in interplanetary space based on the diffusion - convection theory and have qualitatively explained the observed long term variation. These anisotropies produce sector dependant daily variations at the Earth. Moreover, they have pointed out the possibility of observing the phase shifts of the semi and tri-diurnal variations for the transition of the polarity state.

It is noteworthy that these anisotropies are not symmetric for an arbitrary rotation around the IMF-axis. In other words, they cannot be expressed in terms of only the pitch angle with respect to the IMF-axis and therefore cannot be derived from an alternative theory proposed by Bieber and Pomerantz (1983) on the basis of the diffusion of the pitch angle distribution along the IMF-axis (Earl, 1976). In this respect, observation of these anisotropies gives a decisive clue for determining which theory is more suitable for an explanation of cosmic ray anisotropies of solar origin.

The existence of ordered interplanetary field configurations with a radial dimension of the order of 0.25 AU at 1 AU, characterised by higher than average field strengths and a rotation of the field vectors parallel to a plane, was demonstrated by Burlaga and Klein (1980) and Burlaga et.al. (1981) who called them 'magnetic clouds' following an idea proposed by Morrison (1954). A statistical study of magnetic clouds at 1 AU showed that during the period from 1967 to 1978 they occurred at the rate of at least one every three months and that their average radial dimension was 0.25 AU (Klein and Burlaga, 1982).

In magnetic clouds at 1 AU the pressure, principally due to the high magnetic field strengths, is gnerally higher than the ambient pressure, suggesting that they might be expanding as they move away from the Sun. In fact, Klein and Burlaga (1982) argued that between the Sun and 1 AU magnetic clouds expand at a rate of approximately one-half of the local Alfven speed in the directions transverse to $\vec{B}$. If this expansion continues beyond 1 AU, one should find that the radial dimension of magnetic clouds beyond 1 AU should be larger than 0.25 AU, assuming that clouds are stable enough to maintain their identity beyond 1 AU. Specifically the magnetic clouds possess the following characteristics:

(1) a duration of approximately 1 day, corresponding to a characteristic dimension $\simeq$0.25 AU;

(2) the magnetic field direction changing from large southern (northern) directions to large northern (southern) directions, and in some cases back again to the original direction;

(3) magnetic field strength higher than average ($\gtrsim$ 10γ).

In this Chapter we shall analyse mainly the behaviour of the diurnal anisotropy during the days on which Earth is engulfed by the magnetic clouds. Our analysis covers the period from 1967 - 1978, during which 46 magnetic clouds, identified by Klein and Burlaga (1982), were observed at the Earth. Most of the clouds produce Forbush type decreases, hence our main interest is ~~to study the~~ diurnal variation under disturbed interplanetary conditions which are produced by the passage of these magnetic clouds.

4.2 METHOD OF ANALYSIS

As we wished to include in our study the variation of diurnal anisotropy during the passage of the magnetic clouds over the Earth which often produces temporal world-wide decreases we were led to remove these world-wide decreases from the neutron monitor time record. This removal can be accomplished by the use of numerical filtering technique over a single station. We have found that numerical filtering of the data from a single station is simple and more convenient for our purpose, conserving at the same time the essential characteristics we wished to play. The filtering technique used to separate diurnal and wolrd-wide components from the neutron monitor time records has been described previously in detail in Chapter II in the thesis. The data of Deep River neutron monitor has been filtered with the help of Alert neutron monitor.

The 45 magnetic clouds identified by Klein and Burlaga (1982) have been subdivided into three classes by themselves These are: (1) cloud preceded by a shock (2) cloud followed by a stream interface (3) cloud associated with a CME (a region in which the plasma temperature is anomalously low and the magnetic field strength is enhanced.). There are approximately equal numbers of clouds in each class.

When the front boundary of the cloud touches the Earth or Earth's orbit, we arranged that day as the key-day i.e. the arrival day of the cloud on the Earth. Then we took five days before and 5 days after the arrival of the cloud. Thus for all three categories of clouds the data was arranged from -5 to +5 days from the key-day. Chree-epoch analysis is performed to get the decreases. After removing the world-wide component from the data, we analysed the filtered data by harmonic analysis for each set to calculate the diurnal amplitude and phase.

We have also analysed the data for the maximum stay of the clouds on the Earth and for total duration of stay of the clouds on the Earth. Average of A_p index for the days regarding each class of clouds was also obtained from -5 to +5 days taking arrival, maximum duration and total duration days as key-days. The graphs are plotted showing the relation between diurnal amplitude, phase and A_p index.

4.3 RESULTS AND DISCUSSION

In Figure 4.1 we have shown the superposed epoch plots of cosmic ray intensity data from the Deep River neutron monitor corresponding to three classes of clouds. It is found that the decrease in cosmic ray intensity, with the clouds preceded by a shock, is higher in comparison to the decreases observed in association with the other two classes of clouds and the decrease starts earlier than the arrival of the clouds. Moreover, recovery is complete in nearly a week. The decrease in cosmic ray intensity in relation to the clouds followed by

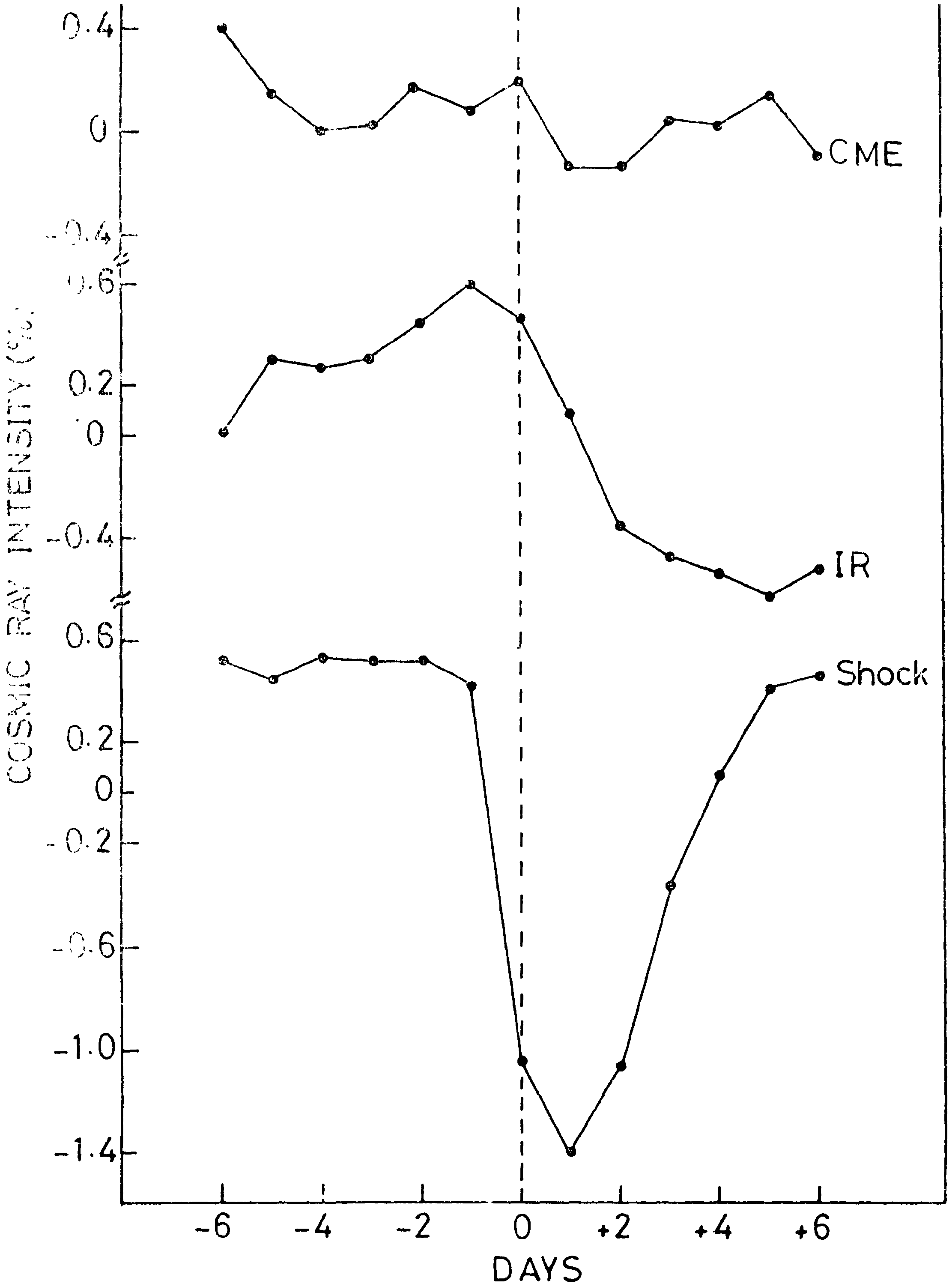


Fig. 4.1 Cosmic ray intensity reduction by three classes of clouds. Zero day is the arrival day of the clouds.

a stream interface is much smaller than the one mentioned above. The decrease time is also elevated and the onset of the decrease takes place on the arrival of the cloud. The decrease observed in association with the third category of clouds, i.e., clouds associated with cold magnetic enhancement is of still smaller amplitude and duration. However, in this also, the decrease in cosmic ray intensity starts when the cloud arrives at the Earth (Badruddin et.al. 1986). However, our main interest here is to find out diurnal anisotropy and discuss it in detail.

The diurnal amplitude (%) and phase (LT) of three category of clouds viz.

(i) Clouds preceded by a shock or shock associated clouds in which the direction of the magnetic field of the front boundary is southward (+) and magnitude of magnetic field 12 γ (table 4.1)

(ii) Clouds followed by stream interface or clouds associated with interaction region (IR) in which nearly two third (2/3) clouds have southward (+) magnetic field and one third (1/3) clouds have northward (-) magnetic field and magnitude of this field is nearly 12 γ (table 4.1)

and (iii) Clouds associated with a CME (Cold magnetic enhancement) in which the direction of the magnetic field is northward (-) and its magnitude is nearly 12 γ (table 4.1)

have been shown on the harmonic dial in Fig. 4.2 (a,b,c). For comparison the diurnal amplitude and phase for geomagnetically quiet days during the years (1967-1978) have also been shown

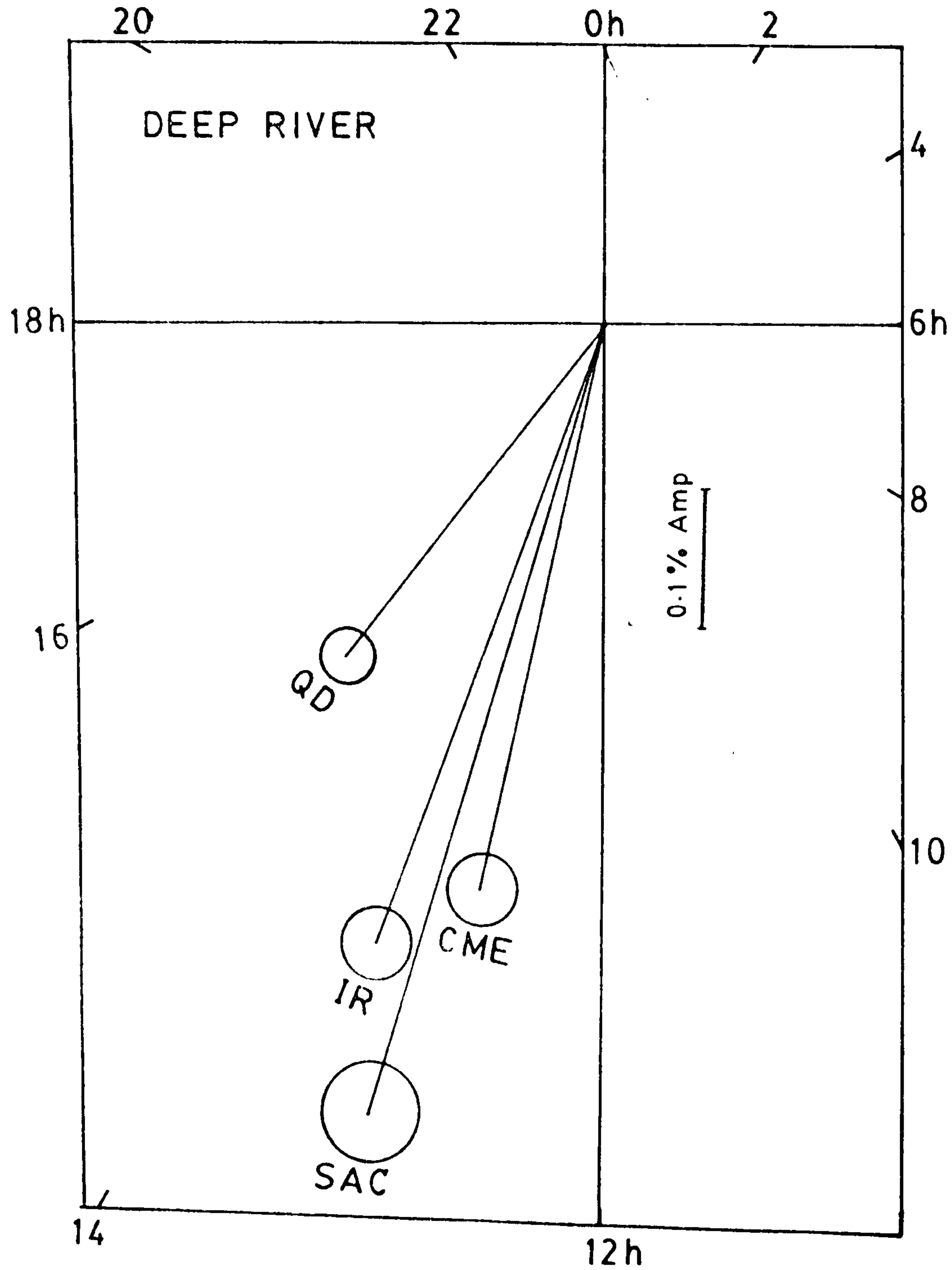


Fig. 4.2 (a) Diurnal amplitude and phase on harmonic dial for three classes of clouds. Zero day is the arrival day of clouds on the Earth.

SAC : Shock associated clouds
IR : Interaction region associated clouds
CME : Cold magnetic enhancement associated clouds
QD : Quiet days.

TABLE 4.1

Average properties of different types of clouds

S.No.	Cloud type	Number	Average field γ	Average speed Km S^{-1}	Average travel time hrs.	Mean duration hrs.	Associated Cosmic ray decrease (%)	Direction of the magnetic field in the front boundary.
1.	Shock associated	14	12	460	90.6	26.6	1.8	Southward (+)
2.	Interface associated	16	12	411.1*	105.0*	20.8*	1.0	Mixed 2/3 southward (+) and one third northward (-)
3.	Cold magnetic enhancement associated	16	12	383.4*	109.9*	30.0*	0.35	Northward (-)

* From Wilson and Hildner (1984)

on the same harmonic dial.

It is apparent from the table 4.2 and Fig. 4.2 (a) that the amplitude for shock associated clouds (SAC) is largest (0.6% $\pm$ 0.03) while for the clouds associated with cold magnetic enhancement (CME) is least (0.4% $\pm$ 0.02) and for the clouds associated with interaction region (IR) is in between the two (0.48 $\pm$ 0.02). Thus we see that the diurnal amplitude for all three category of clouds is higher in comparison with the diurnal amplitude of geomagnetically quiet days. Fig. 4.2 (a) and table 4.2 shows that the phases for shock associated clouds (SAC), clouds associated with interaction region (IR) and clouds associated with cold magnetic enhancement (CME) are 13.1 hrs, 13.4 hrs and 12.8 hrs respectively. We see that there is clearcut phase shift towards earlier hours in comparison to the phase of geomagnetically quiet days (Table 4.2). Figure 4.2 (a) and table 4.2 also shows that the differences of the diurnal amplitudes and phasesare significant for all three categories of clouds in comparison with quiet days values as well as among themselves also. These values of diurnal amplitude and phase have been obtained on the day when respective category of clouds reaches on Earth (or Earth's orbit).

Fig. 4.2 (b) shows the diurnal amplitude and phase on the day when the respective category of clouds remained for maximum time on the Earth i.e. the zero day was taken the maximum duration day of the respective category of clouds. We see that there is not much difference between these values and values obtained on the arrival day of the clouds. Although the

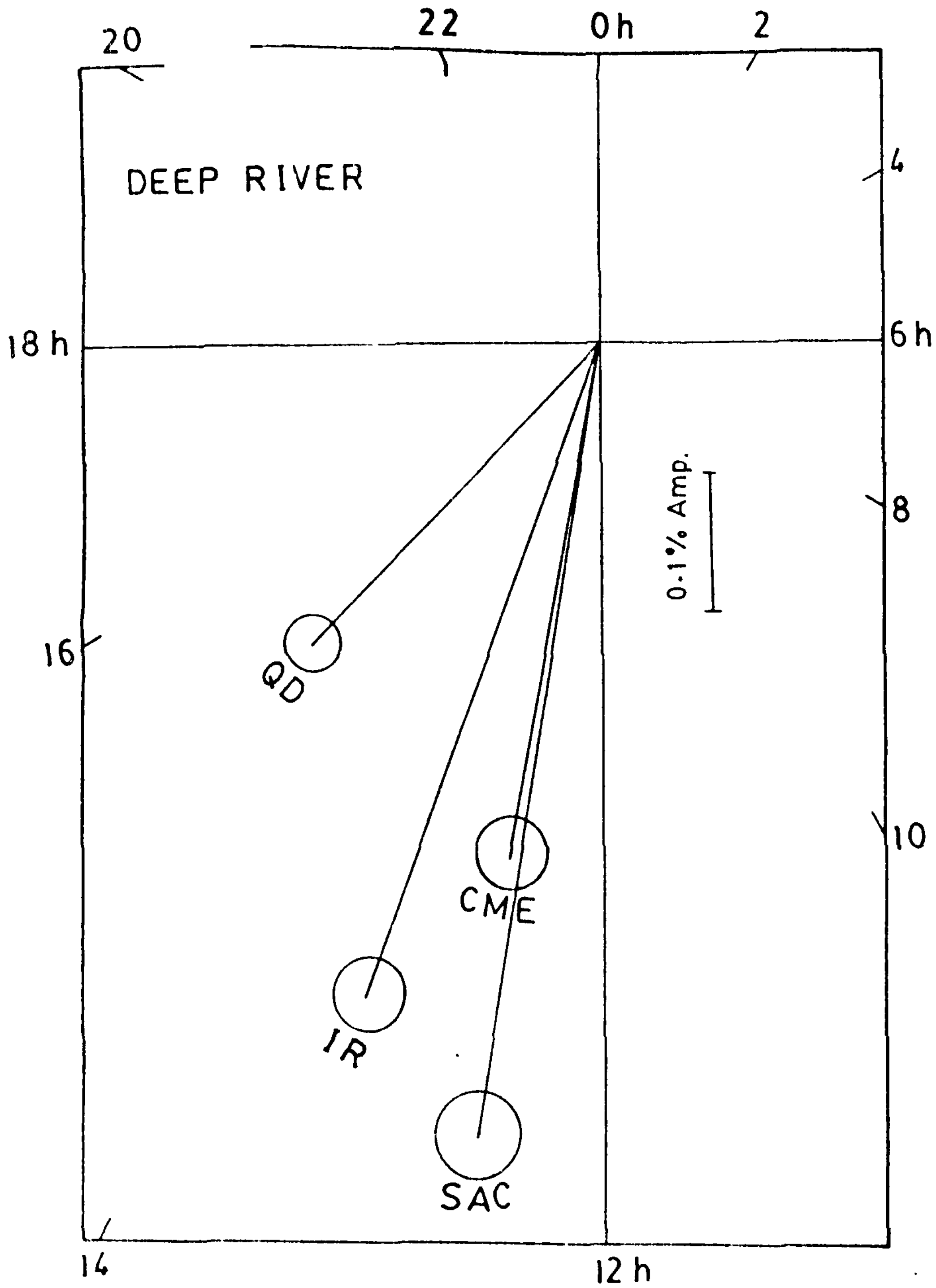


Fig. 4.2 (b) Same as Fig. 4.2(a). Zero day is the maximum duration of stay of these clouds on the Earth.

TABLE 4.2

The diurnal amplitude and phase for three category of clouds at Deep River

S.No.	Category of clouds	Zero day is the arrival day of cloud (a)		Zero day is the maximum duration day of the cloud (b)		Zero day is the total duration of the cloud (c)		Remark
		Amplitude % at ground.	Phase hours (LT) at ground.	Amplitude % at ground.	Phase hours (LT) at ground.	Amplitude % at ground.	Phase hours (LT) at ground.	
1.	Shock associated cloud (SAC)	0.6 ± 0.03	13.1 ± 0.14	0.58 ± 0.03	12.6 ± 0.12	0.47 ± 0.02	12.6 ± 0.12	
2.	Clouds associated with interaction region (IR)	0.48 ± 0.02	13.4 ± 0.16	0.50 ± 0.02	13.3 ± 0.16	0.45 ± 0.02	13.3 ± 0.15	
3.	Clouds associated with cold magnetic enhancement (CME)	0.4 ± 0.02	12.8 ± 0.12	0.38 ± 0.02	12.7 ± 0.12	0.42 ± 0.02	12.7 ± 0.12	
4.	Quiet days	0.30 ± 0.02	15.0 ± 0.19					

phase of shock associated clouds and clouds associated with cold magnetic enhancement becomes nearly equal as is clear from the Fig. 4.2 (b) and table 4.2.

Fig. 4.2 (c) shows the diurnal amplitude and phase of the total duration of the clouds remaining on the Earth, the zero day is considered as the days for total duration days of clouds. Here we see that the amplitudes of three category of clouds reach nearly equal values i.e. there is not much difference among themselves but the amplitudes are higher in comparison to quiet days amplitude. Although the phases are very close to the value of Fig. 4.2 (b).

Now these results are discussed in the light of available results and theories. The anisotropies are determined by the instantaneous conditions in the interplanetary space, and it is of interest here to examine this relationship between cosmic ray density, interplanetary magnetic field and anisotropy, and to infer the cause of the observed anisotropies.

The expression for the differential cosmic ray current density $\vec{S}$ is given (Pomerantz and Duggal, 1971; Forman and Glesson, 1975) by

$$\vec{S} = \vec{S}_c - K_{||}\left(\frac{\partial u}{\partial \vec{r}}\right)_{||} - K_{\perp}\left(\frac{\partial u}{\partial \vec{r}}\right)_{\perp} - \frac{v^2(\omega\tau)^2}{3\omega(1+(\omega\tau)^2}\left[\frac{\partial u}{\partial \vec{r}} \times \frac{\vec{B}}{B}\right] \quad \ldots. \; (4.1)$$

$$\vec{S}_c = C_G U\vec{V}$$

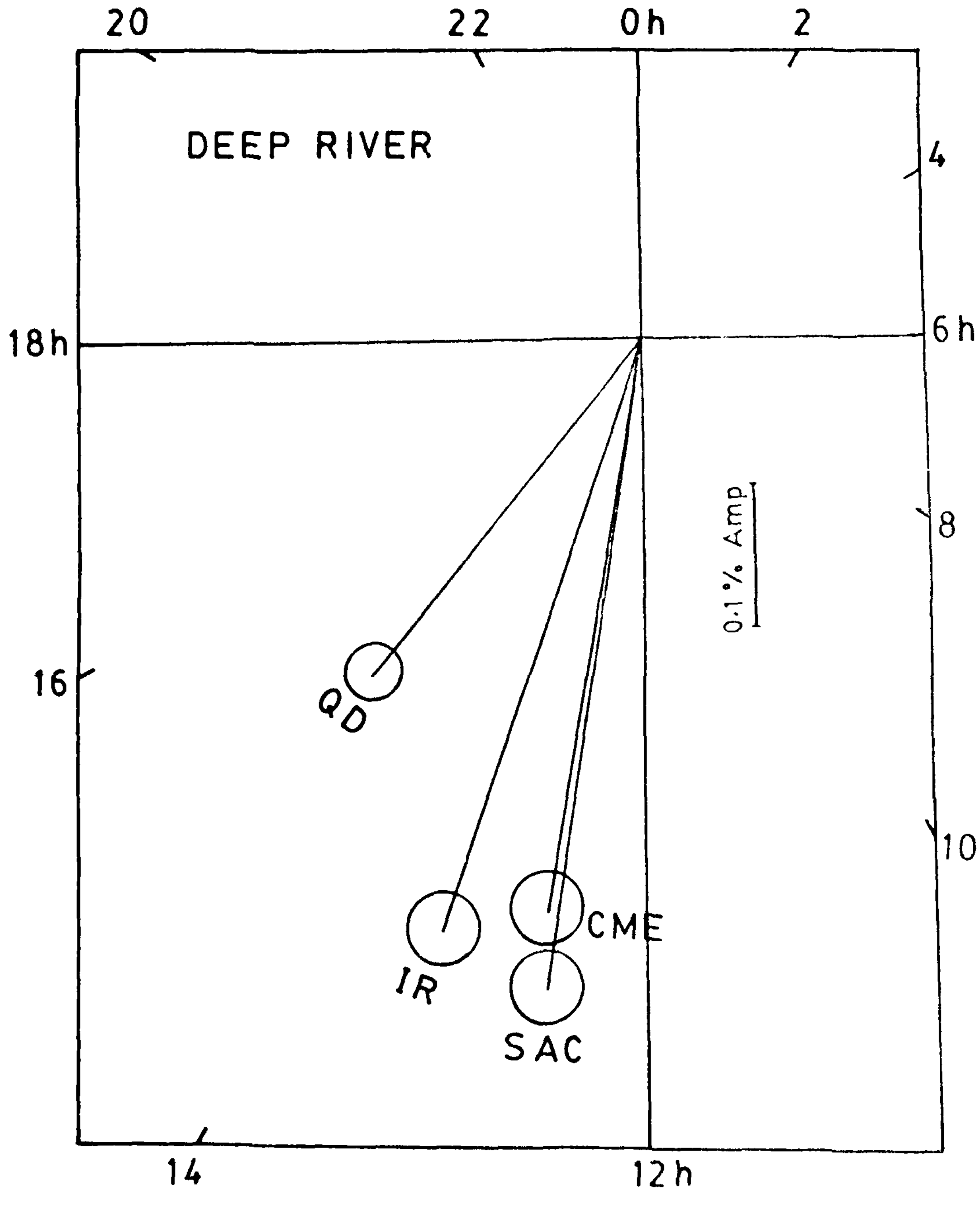


Fig. 4.2 (c) Same as Fig. 4.2(a). Zero day is the total duration of the stay of these clouds on the Earth.

where

C_G = Compton - Getting factor (~ 1.5)

U = differential number density

$\vec{V}$ = Solar wind velocity

$\vec{B}$ = magnetic field (IMF)

$K_{||}$ = diffusion coefficient parallel to IMF $\vec{B}$

$K_{\perp}$ = diffusion coefficient perpendicular to IMF $\vec{B}$

ω = 2π(gyrofrequency)

τ = Collision time

v = Speed of the cosmic ray particles.

The first term on the right of equation 4.1 is the convective component, the next two are diffusive components and last is a component due to the density gradient.

The anisotropy vector $\vec{\xi}_1$ is related to $\vec{S}$ by

$$\vec{\xi}_1 = \frac{3\vec{S}}{vu} \qquad \text{.... (4.2)}$$

and introducing the gyroradius ρ, the convective anisotropy $\vec{\xi}_{1c}$ and the vector gradient $\vec{G}$ defined below

$$\left.\begin{aligned} \vec{\xi}_{1c} &= \frac{3\ C_G\ u\vec{V}}{vu} = \frac{3\ C_G\ \vec{V}}{v} \\ \vec{G} &= \frac{1}{u}\left(\frac{\partial u}{\partial \vec{r}}\right) \end{aligned}\right\} \qquad \text{.... (4.3)}$$

we obtain from equation 4.1 and 4.2, the convenient form as follows:

$$\frac{3\vec{S}}{vu} = \frac{3\vec{S}_c}{vu} - \frac{3K_{||}}{vu}\left(\frac{\partial u}{\partial \vec{r}}\right)_{||} - \frac{3K_{\perp}}{vu}\left(\frac{\partial u}{\partial \vec{r}}\right)_{\perp} - \frac{3v^2}{3\omega\ vu}\frac{(\omega\tau)^2}{1+(\omega\tau)^2}\left[\frac{\partial u}{\partial \vec{r}} \times \frac{\vec{B}}{B}\right]$$

$$\vec{\xi} = \vec{\xi}_c - \frac{3K_{||}}{v}\vec{G}_{||} - \frac{3K_{\perp}}{v}\vec{G}_{\perp} - \frac{(\omega\tau)^2}{1+(\omega\tau)^2}\rho\vec{G} \times \frac{\vec{B}}{B} \quad \text{.... (4.4)}$$

This may also be written as

$$\vec{\xi} = \vec{\xi}_c + \vec{\xi}_{||} + \vec{\xi}_{\perp} + \vec{\xi}_{\vec{G}} \quad \text{.... (4.5)}$$

The successive terms being due to convection (radially outward), parallel diffusion, perpendicular diffusion and the density gradient current.

$K_{||} = \frac{\lambda v}{3}$ [λ = mean scattering free path]

$K_{\perp} = \frac{1}{1+(\omega\tau)^2} K_{||}$

$\vec{\omega} = \frac{q\vec{B}}{mc}$

$\rho = \frac{pc}{qB}$ [p = particle momentum]

It is useful here to have a set of typical quiet time values for the above quantities in mind. With $V = 400$ Kms/Sec, the rigidity R in gigavolts (GV), B in gammas and $\beta = \frac{v}{c}$, these values are

$\xi_c = 0.6\%$ .... (i)

$K_{||} = 6 \times 10^{21}\ R\beta\ \text{Cm}^2/\text{Sec}$ ... (ii)

$\frac{K_{\perp}}{K_{||}} \leq 0.1$

$$\frac{3K_{||}}{v} = \lambda \simeq 6 \times 10^{11}\ R\ \text{Cms} = 4 \times 10^{-2}\ R\ \text{AU}$$

$$G = \frac{30}{R\beta} \simeq \frac{30}{R}\%\ \text{per AU} \qquad \text{.... (iii)}$$

directed radially outward

$$G_{||} = G \cos 45^{o} \simeq \frac{30}{R} \times 0.7\%\ \text{per AU} = \frac{21}{R}\%\ \text{per AU}$$

$$\frac{3K_{||}}{v} G_{||} = \xi_{||} \simeq 0.84\%$$

$$\rho = \frac{R}{40\ B}\ \text{AU} \qquad \text{.... (iv)}$$

$$\omega\tau = 8\ ;\ \frac{(\omega\tau)^2}{1+(\omega\tau)^2} \simeq 1 \qquad \text{.... (v)}$$

when $B = 5\gamma$, $K_{||} = 6 \times 10^{21}\ R\beta\ \text{cm}^2/\text{sec}$

and then

$$\frac{(\omega\tau)^2}{1+(\omega\tau)^2} \rho_G \times \frac{\vec{B}}{B} \simeq 0.1 \qquad \text{.... (vi)}$$

Hence the last terms in equations 4.4 and 4.5 are insignificant under quiet time conditions. Here the value for $K_{||}$ is for 1965 (Urch and Gleeson, 1972), and changes for other years are obtained by replacing R by MR in (i), (ii) and (iii) by putting $\omega\tau = 8\ M$ in (iv) and by replacing 0.1 by $\frac{0.1}{M}$ in (vi), with M values of 1, 0.58, 0.42 and 0.37 for 1965, 1968, 1969 and 1970 respectively. Under quiet time conditions, $\vec{\xi}_{\perp}$ and $\vec{\xi}_G$ are insignificant and only $\vec{\xi}_c$ and $\vec{\xi}_{||}$ are significant in equation 4.5 and should be considered.

Variations of three dimensional anisotropy of cosmic rays during Frobush decreases were examined by Yoshida et.al. (1973). They examined the high anisotropy of ($\sim$4%) in terms of the convective, diffusive and density gradient components of the differential streaming as well as the interplanetary magnetic field and solar wind. Based on the flow of the particles due to convection, diffusion and gradient effects, they provided possible explanations for high ($\sim$4%) anisotropies observed during Forbush decreases. Their significant conclusion is that density gradients are required that are transverse to the magnetic field and these have magnitudes of the order of 10 - 20 times the quiet time gradients. Hence it is clear that the last terms of equations 4.4 and 4.5 are also significant and $\vec{\xi}_{\perp}$ and $\vec{\xi}_{G}$ should also be considered.

Barouch and Burlaga (1975) have reported that the high magnetic field regions ('blobs') in the interplanetary space are associated with Forbush decreases. Duggal and Pomerantz (1983) concluded that modulations produced by changes in IMF intensity alone are significant. Abnormally high values of this IMF parameter ($B > 8\ \gamma$) produce cosmic ray intensity decreases, the magnitudes of which is related to the extent of the departure of B from average. Barouch and Sari (1976) further demonstrated that these cosmic ray decreases are not related to the turbulence and random motions in the field and that only the large scale features of the interplanetary magnetic field (IMF) are important.

The formation of density gradient perpendicular to the ecliptic plane is discussed below. As the cloud moves outward, it 'sweeps away' the cosmic ray particles ahead of it. Since one only occassionally observes enhancements before a Forbush decrease, it is possible that the particles are deflected out of the ecliptic. One can form conceptual images of several ways in which the particles could be deflected out of the ecliptic plane. One of these is gradient drift.

Since the scale length of the cross-section of the cloud is L 0.25 AU, particles with rigidities upto 100 GV can be deflected. Since the magnetic field intensity increases from 5 γ to 12 γ and in some cases upto 35 γ in a cloud, the gradients are of the order of 100 γ/AU. As a consequence of shearing in $\vec{B}$, the perpendicular drift appears. Such a high gradient ($\sim$100 γ/AU) in the cloud causes the particle to drift with the velocity

$$\vec{v}_D = \frac{c}{q}\left(\frac{W_\perp}{B}\right)\left(\frac{\vec{B} \times \nabla B}{B^2}\right)$$

[Northrop, 1963, Parker, 1957, 1963]. Here $W_\perp$ is the kinetic energy of the particle perpendicular to $\vec{B}$. The direction of $\vec{V}_D$ is perpendicular to both $\vec{B}$ and grad $|\vec{B}|$. For the interplanetary magnetic field both $\vec{B}$ and grade $|\vec{B}|$ are situated in the ecliptic plane, so that $\vec{V}_D$ is perpendicular to ecliptic plane. Let $L = 1\rho$ where 1 is the number of steps and ρ is the gyroradius. For a 1 GeV proton in a 20 γ field, $\rho \simeq 0.01$ AU and for $\frac{L}{2} \simeq 0.13$ AU, $1 = 13$. Nothing that

$$W_{\perp} = \frac{qv_{\perp}\rho B}{2c} \simeq \frac{qcBL}{21c}$$

One finds that

$$V_D = \frac{c}{25}$$

This drift velocity is much larger than the rate at which the cloud advances ($\frac{V_D}{v_w} = \frac{c}{25\ v_w} \simeq 30$, where v_w is the speed of the cloud or solar wind velocity). Suppose that a cloud has a square cross-section and extends $\pm \frac{L}{2}$ above and below the ecliptic plane. Assume that the gradients normal to the ecliptic are small, except near the boundaries. As the cloud advances radially outward from the Sun, it engulfs cosmic rays. Since a particle drifts out of the ecliptic much faster than the cloud advances, it is effectively removed from the region swept out by the cloud and is deposited somewhere near the top or bottom of the cloud depending upon the sign of $\vec{B}$ and ∇B. This mechanicsm leads to strong N-S gradients normal to the ecliptic. If there is some scattering in the cloud, this might lead to N-S asymmetries in the cosmic ray flux, Pomerantz and Duggal (1972) point out that nearly all Forbush decreases are accompanied by N-S anisotropies. It has been established that anisotropy perpendicular to the plane of ecliptic is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971, 1976; Mercer et.al. 1971). Moraal and Mulder (1985) presented the evidence that the drift effect on the modulation of galactic cosmic rays can be seen on Forbush decreases observed by Deep River neutron monitor.

It has been established that the begining of the change of vector of solar diurnal anisotropy of galactic cosmic rays preceeds the beginning of Forbush decrease which is due to the disturbed region (Naskidashvili et.al., 1985).

Flow perpendicular to the ecliptic plane causes north-south asymmetry in ground observations of cosmic rays and the grad-B drift can be recognised for its characteristic dependence on the polarity of the magnetic field. The result of this drift will be a local redistribution of the cosmic ray number density. Thus a particle density gradient is established perpendicular to the ecliptic. Enhancement of the grad-B drift have also been detected during the Forbush decrease by Yoshida et.al. (1973) and Suda et.al. (1981). Being dependent on the IMF polarity which is toward or away, the transport by the particle density gradient drift should bring cosmic rays toward the ecliptic plane.

It has been demonstrated that the cosmic ray drift motion in the heliosphere produces the change of the cosmic ray density distribution for the transition of the polarity state and, as a result, produces the rise and fall of the axis-asymmetric anisotropies for the observed phase shifts in the solar daily variations (Nagashima et.al. 1986). These phase shifts are due to the change of the cosmic ray density distribution in space caused by the change of the drift motion of the cosmic rays in the heliosphere for the transition of the polarity state, as emphasized by Jokipii et.al. (1977).

One of the method of detecting the cosmic ray distribution perpendicular to the ecliptic is to use the cosmic ray flow in the ecliptic plane arising from $\vec{B} \times \vec{\nabla} U$. If $\vec{B}$ lie in the ecliptic plane, the direction of this flow (in the 3 hr or 15 hr direction) is perpendicular to $\vec{B}$ and depends on the sense of $\vec{B}$. This flow will be superposed on the so-called corotation streaming. If the difference is taken between observed diurnal variations sorted according to the toward (T) and away (A) polarity of IMF, common corotation streaming will be almost cancelled. Then, the resultant T-A vector can represent mainly the field dependent one, and this may be reflected by the behaviour of the perpendicular cosmic ray gradient to the ecliptic plane. Hashim and Bercovitch (1972), Swinson and Kananen (1982), Swinson et.al. (1986) and Badruddin et.al. (1985) have applied this method to the solar diurnal variation data and obtained almost a similar result to the above.

The $\vec{B} \times \vec{\nabla} U$ anisotropy arises as a result of the anti-symmetric term of the diffusion tensor. The magnitude of the resulting anisotropy is $\rho . \nabla_{\perp} U/U$, where $\nabla_{\perp} U$ is the density gradient in the direction normal to the field. Being polarity-dependent this anisotropy can be disentangled from other terms of the anisotropy, and then, knowing the Larmour radius, ρ, the gradient can be determined (Bercovitch, 1970).

4.3.1. Diurnal Amplitude and Phase During The Passage of Shock Associated Clouds

The direction of the magnetic field in the front boundary of the shock associated clouds is southward (+) or away from the Sun with average value of 12 γ nearly. Due to the association with shocks these clouds moves faster than all other category of clouds (Table 4.1). Fig. 4.2 (a,b,c) and table 4.2 shows that the diurnal amplitude of these clouds is largest among all category of clouds.

Patel et.al.(1968) found that the diurnal anisotropy caused by the latitudinal gradients should reverse as the magnetic field or the gradient reverses. When the gradient is such that solar activity north of the equatorial plane is greater than south, the latitudinal gradient should give rise to a diurnal anisotropy with its direction of maximum on the average along 1500 hrs (U.T) when the field is directed away from the Sun (+) and along 300 hrs (U.T) when the field is directed toward the Sun (-). Such an asymmetry will increase the amplitude of the diurnal component due to azimuthal streaming when the field is away (+) from the Sun. This is verified using a set of neutron monitors during IMP-1 period (Wilcox and Ness, 1964) for six solar rotations when interplanetary magnetic field direction in different sectors has been identified.

Ichinose et.al. (1983), following the work by Fujimoto et.al. (1979), used 470 station years of data from the world-wide neutron monitor net work to demonstrate that the field dependent component of the cosmic ray solar diurnal variation, arising from the perpendicular density gradient changed phase significantly. The diurnal component diminished for the negative state while that may exist significantly in the positive state. Also Owens et.al. (1980) proposed that the component of the corotating cosmic ray gradient in the ecliptic plane gives rise to a north-south anisotropy and the component of the corotating cosmic ray gradient perpendicular to the ecliptic gives rise to an anisotropy in the ecliptic seen in the diurnal variation. Mavromichalaki (1981) found that an enhanced mean amplitude of the diurnal anisotropy correlates with positively directed sectors.

The presence of the $\vec{B} \times \vec{\nabla} U$ streaming was also demonstrated in the work of Takahashi et.al. (1985) who deduced the first zonal harmonic from the data of the world-wide neutron monitor net work, and showed that it undergoes sudden jumps at sector crossings. A good correlation was found between the anisotropy and the component of the magnetic field by Xue et.al. (1985). The $\vec{B} \times \vec{\nabla} U$ anisotropy can also be applied to detect a steady north-south gradient as it has been shown by Swinson et.al. (1986). The $\vec{B} \times \vec{\nabla} U$ streaming, in this case, adds a polarity dependent component to the daily variation in solar time.

Taking zeroth day as the arrival day of the shock associated clouds the A_p index, diurnal amplitude and phase have been plotted in the upper, middle and lower panels of the Fig. 4.3 (a) from -5 to +5 days. It is clear from the middle panel that there is no appreciable change in the dirunal amplitude from -5 to -2 day from the zeroth day. The increase in diurnal amplitude at -1 day from the zero day is clearly indicating the arrival of the shocks which are coming ahead of the cloud. The maximum increase of diurnal amplitude on zero day indicates the effect of the genuine

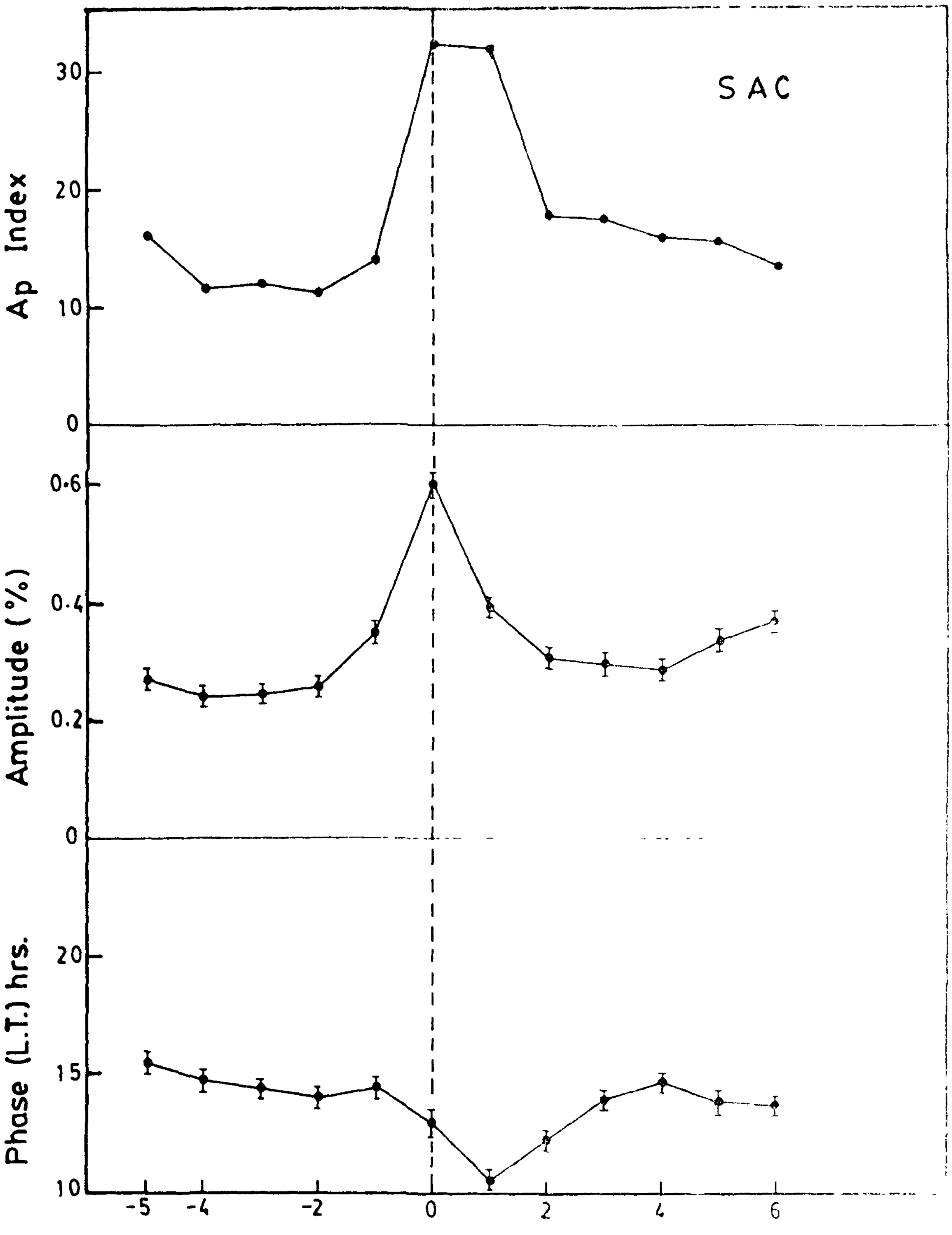


Fig. 4.3(a) Superposed epoch analysis results for $\pm$ 5 days about zero day of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively for shock associated clouds. (SAC). Zero day is the arrival day of these clouds on the Earth.

disturbance caused by these clouds. On +1 day (i.e. after one day of the arrival of the clouds), the diurnal amplitude decreases. On +2 day and onward the diurnal amplitude returns back to slightly greater values and remains constant for further 3 days in comparison to the days before the arrival of the shocks and clouds. In the upper panel the behaviour of A_p values is shown. These values show the similar behaviour like diurnal amplitude. Although the value of A_p on zero day and +1 day remains almost constant while diurnal amplitude on +1 day decreases. A clearcut phase shift towards earlier hours in comparison to -1 day or earlier days is seen on the lower panel of Fig. 4.2(a). The recovery of phase starts after +2 day and recovers on + 3 day and then remains constant as before the arrival of the cloud.

In Fig. 4.3(b) the A_p index, diurnal amplitude and phase have been plotted on the upper, middle and lower panels respectively from -5 to +5 days from the zeroth day. Here the zero day have been taken as the day on which the duration of the stay of these clouds on Earth remained maximum i.e. maximum duration days. In this figure the behaviour of A_p, diurnal amplitude and phase is more clear on the zeroth day. Rest of the behaviour is as in the Fig. 4.3(a).

Fig. 4.3(c) have been plotted by taking zeroth day as the days for total duration of stay of these clouds on the Earth. Although the magnitude of the diurnal amplitude has decreased while the phase and A_p values remained as in fig. 4.3(b).

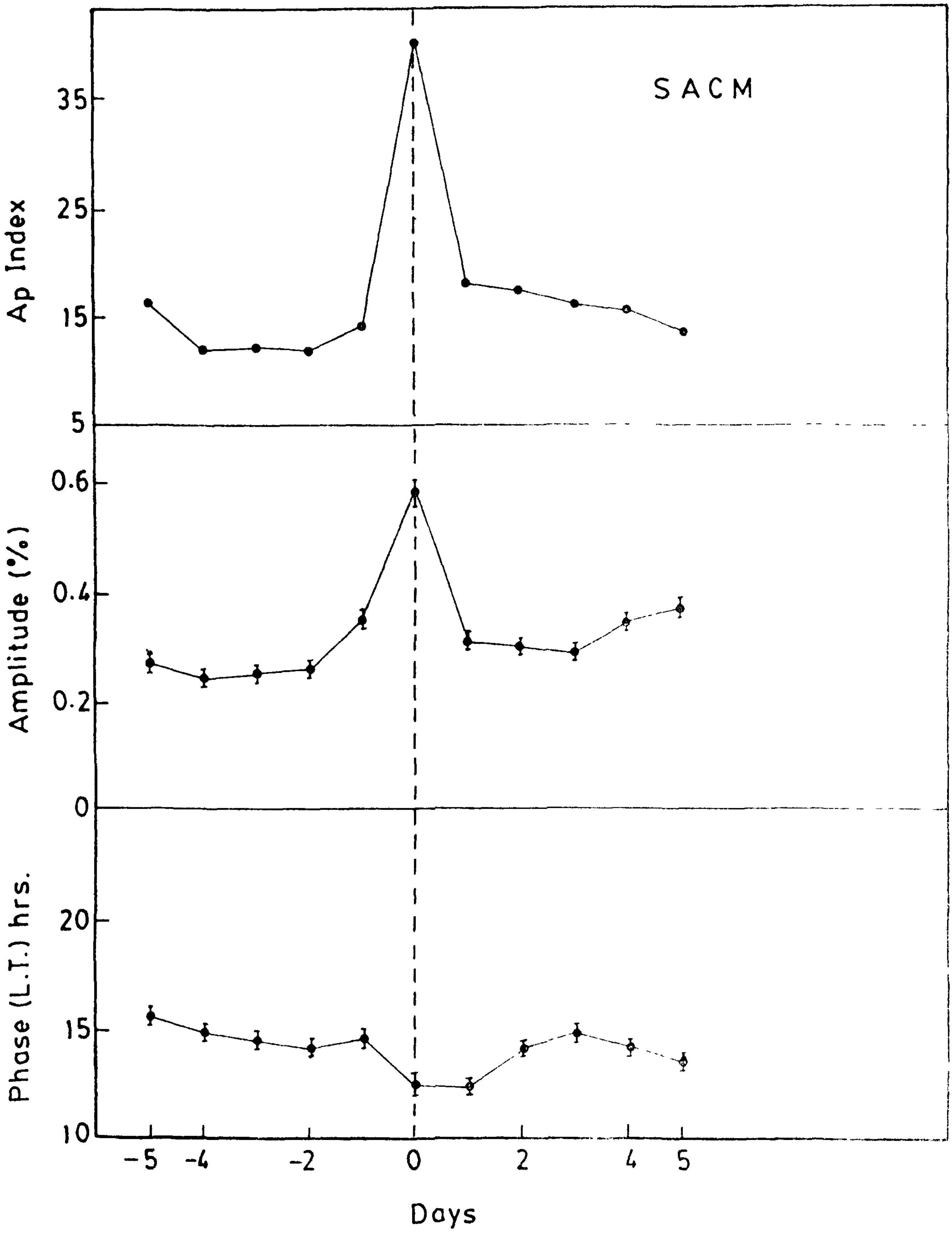


Fig. 4.3(b) Same as Fig. 4.3(a). Zero day is the maximum duration of stay of these clouds on the Earth (SACM).

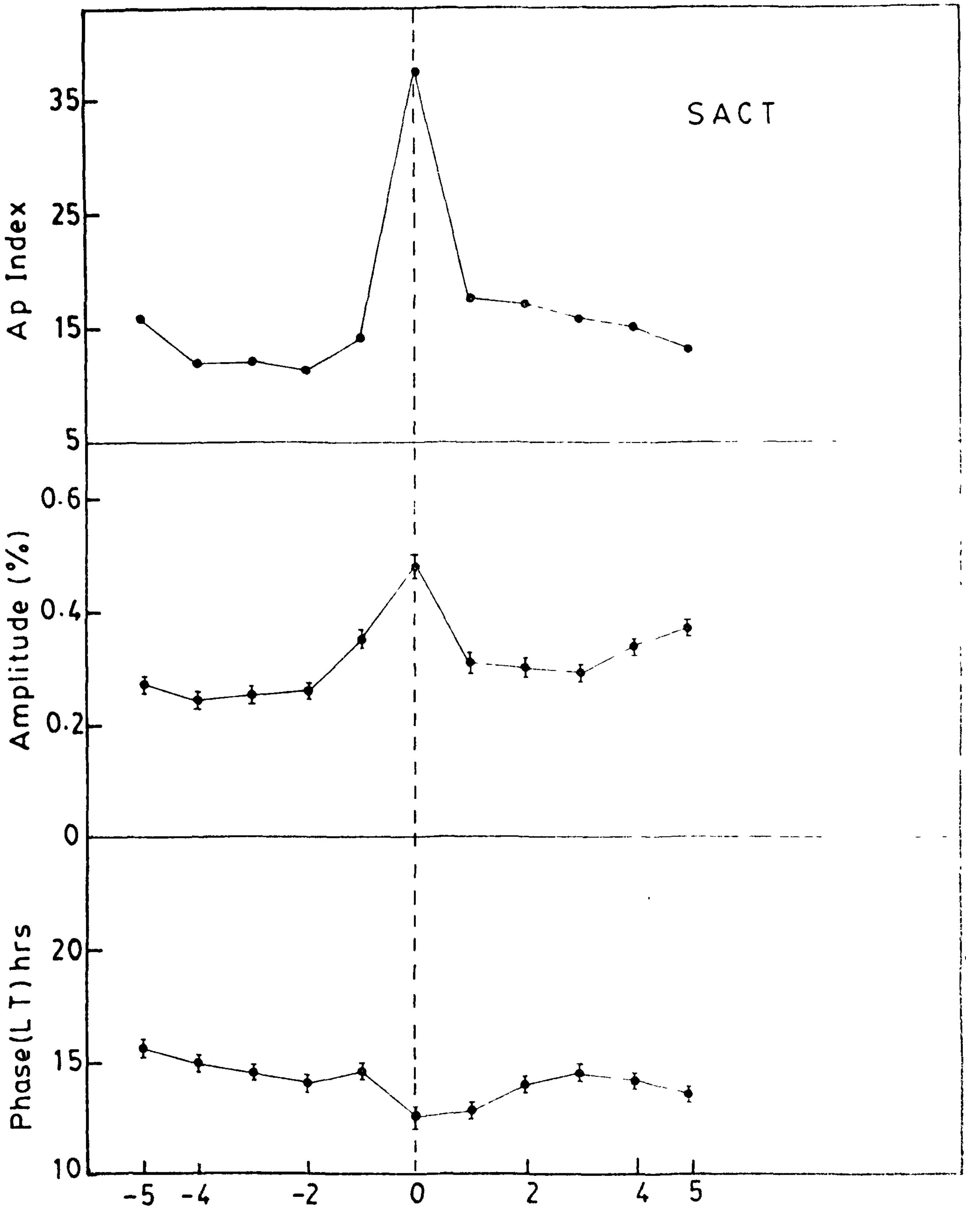


Fig. 4.3(c) Same as Fig. 4.3(a). Zero day is the total duration of stay of these clouds on the Earth (SAC T).

Recently, Kadokura and Nishida (1986), in the theoretical calculation of two-dimensional numerical modeling of the cosmic ray storm, showed that preceding the arrival of the shock, the phase shifts to the earlier hours and the amplitude becomes large which is compatible with observations of Wada and Suda (1980). Both phase and amplitude return to almost the undisturbed value when the solar wind disturbance has passed, while the cosmic ray density perturbation remains. Our observations during the disturbance caused by the magnetic clouds is more or less in agreement with the above prediction made on the basis of theoretical calculation by Kadokura and Nishida (1986).

4.3.2 Diurnal Amplitude and Phase During The Passage of Clouds Followed by Interaction Region

Fig. 4.4(a) shows the plots of A_p index, diurnal amplitude and its phase on upper, middle and lower panels respectively from -5 to +5 days from zero day. The zeroth day is taken as the arrival day of these category of clouds. It is seen from the upper and middle panels of this figure that A_p value and diurnal amplitude are higher at zero-day in comparison to the -1 day i.e. before arrival of the clouds. The decrease in diurnal amplitude on +1 day shows that duration of stay of these clouds on Earth is short i.e. less than one day (table 4.1). It is seen from the upper panel of this figure that A_p increases much on +1 day showing the fact that the magnetic field and solar wind velocity increase gradually and it is largest at the rear boundary of these clouds. Since these clouds are followed by interaction region which arrives after 12 to18

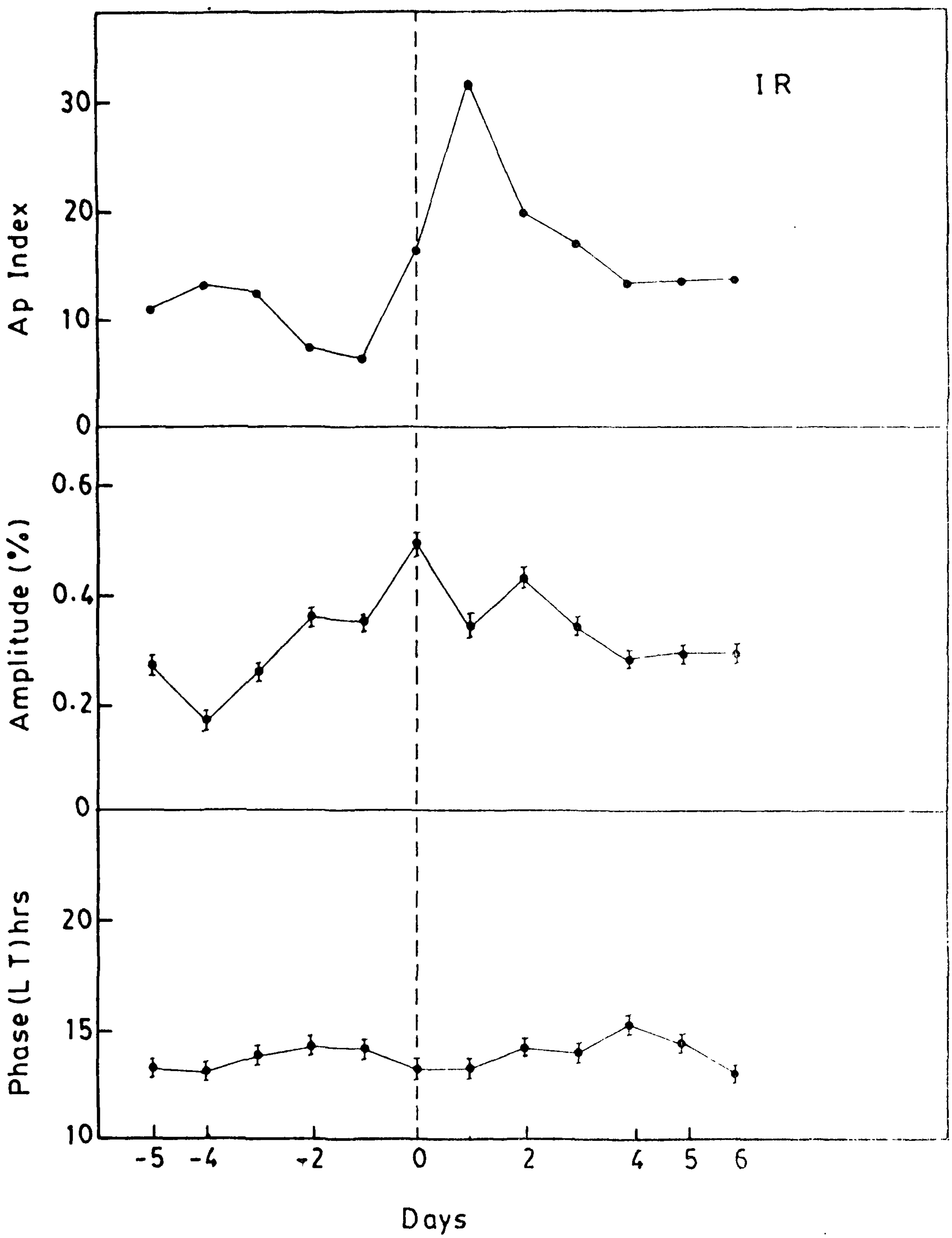


Fig. 4.4(a) Superposed epoch analysis results for ± 5 days about zero day of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively for interaction region (IR) associated clouds. Zero day is the arrival day of these clouds on the Earth.

hours from the departure of the clouds from the Earth. Hence the magnetic field remained enhanced while solar wind still increases due to interaction region (Klein and Burlaga, 1982) and its effect is clearly seen on +2 day in the figure 4.4 (a) in the diurnal amplitude which again increases in comparison to +1 day and even -1 day. After the removal of the clouds and interaction region the diurnal amplitude recovers on +3 day and remains constant onward. The lower panel of this Fig. 4.4(a) shows the phase shift towards earlier hours on zero-day. The phase recovers after the removal of the disturbance due to clouds and interaction region from +3 day and onward. Here again our observations are in agreement with the theoretical calculations of Kadokura and Nishida (1986) on the two-dimensional numerical modeling on cosmic ray storms.

In Fig. 4.4(b) the maximum duration of stay of these clouds on the Earth is taken as zero day and A_p index, diurnal amplitude and phase are plotted on upper, middle and lower panels respectively from -5 to +5 days from the zero day. The features are similar as in fig. 4.4(a) above with a slight decrease in the magnitude of A_p on zero day. The effect of interaction region (IR) is visible in the diurnal amplitude (middle panel of fig. 4.4(b)) here also on +1 day which is the arrival day of interaction region which comes behind the clouds.

Fig. 4.4(c) shows the plots of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days from zero day. The zero day here is taken as the total

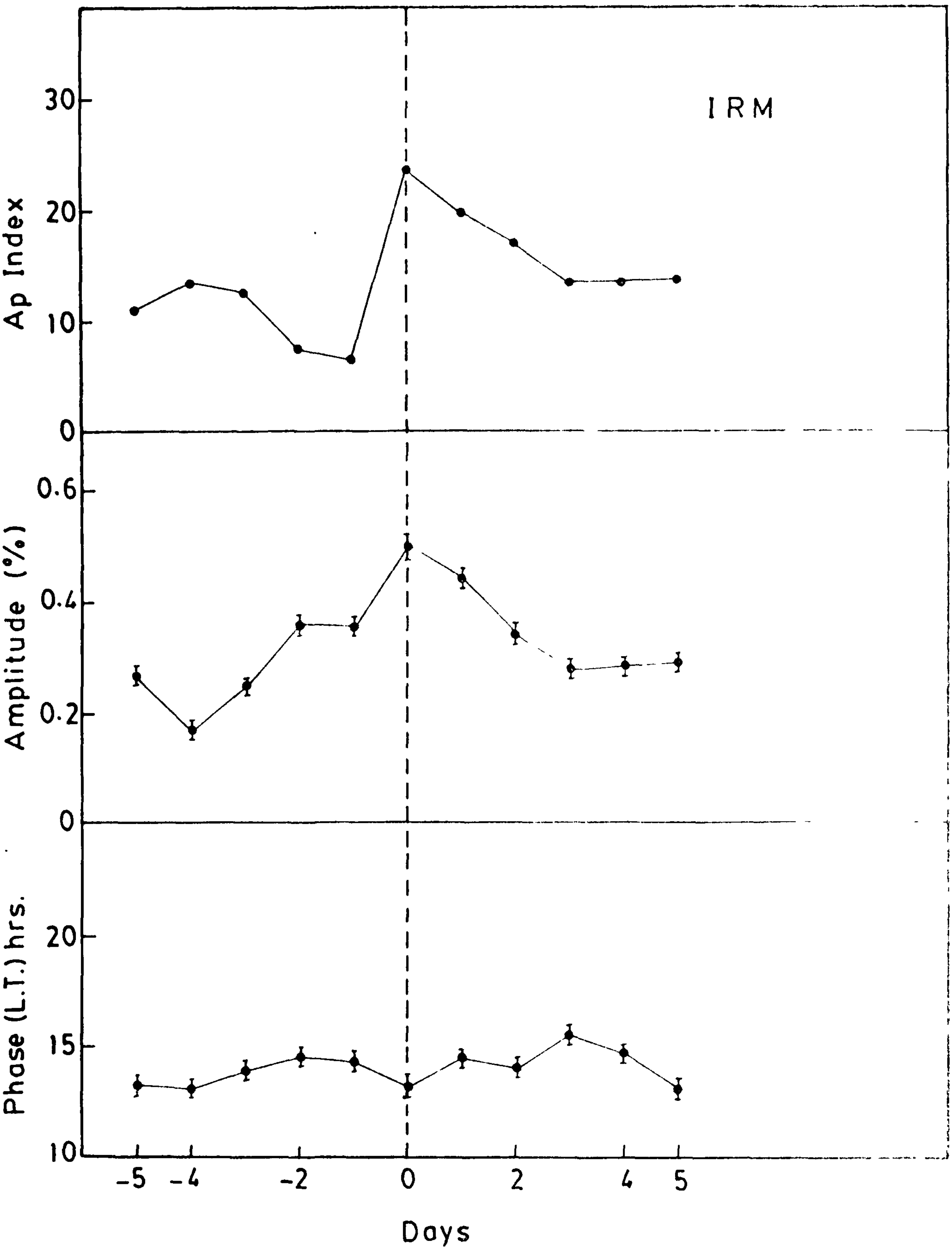


Fig. 4.4(b) Same as Fig. 4.4(a) is the maximum duration of stay of these clouds on the Earth (IRM).

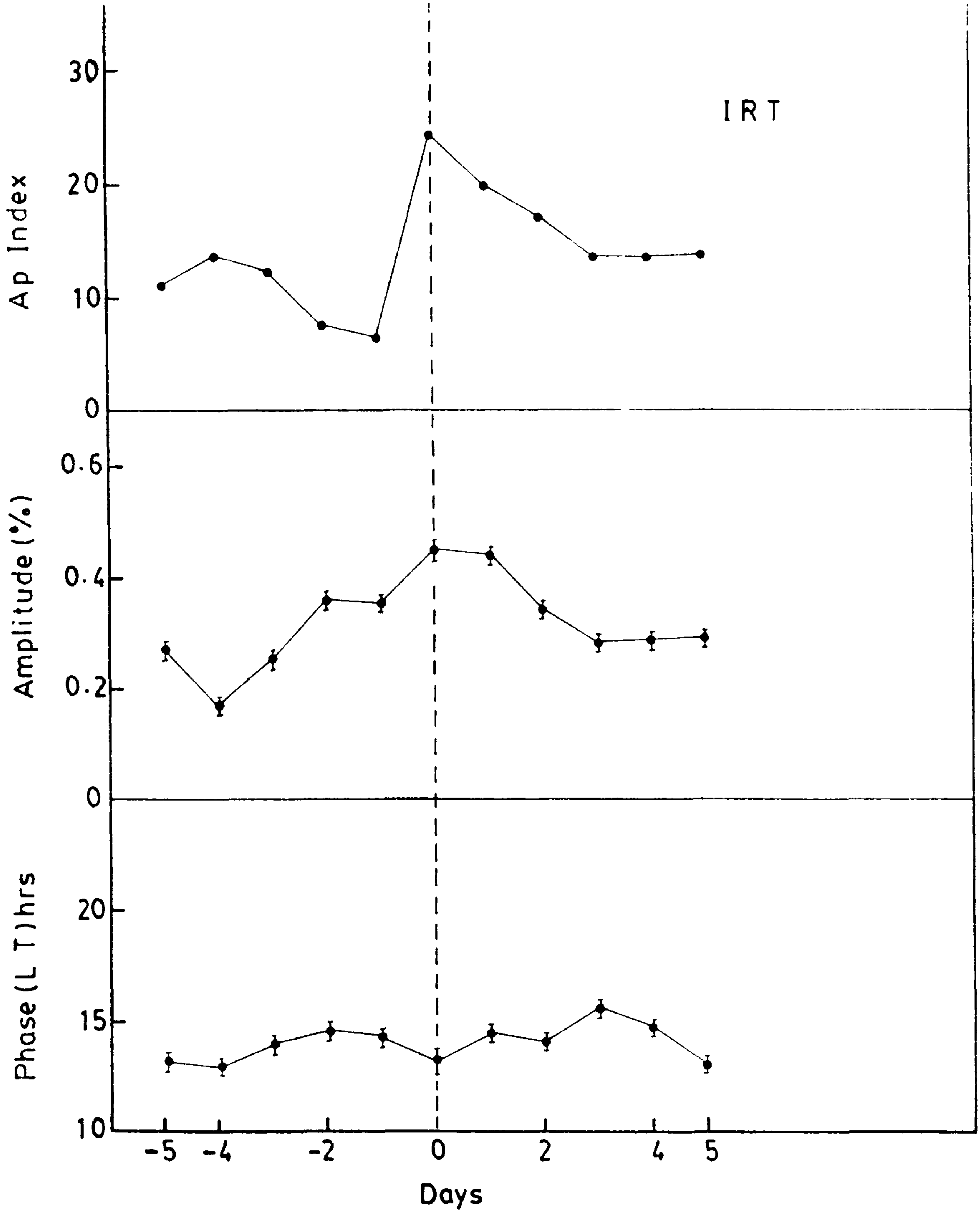


Fig. 4.4(c) Same as Fig. 4.4(a). Zero day is the total duration of stay of these clouds on the Earth. (IRT).

duration of stay of clouds on the Earth. The features here are similar to figure 4.4(b) with slight decrease in the magnitude of the diurnal amplitude on zero-day.

Nearly two third of the clouds in this category have the magnetic field southward (+) while one third of the clouds have northward (-) in their front boundary. Hence the diurnal amplitude is less than the shock associated clouds which have magnetic field southward (+) and large than cold magnetic enhancement (CME) associated clouds which have northward (-) magnetic field as is seen from the figure 4.2(a) and table 4.2. Thus these clouds behave just like as a mixed flow behaves. The perpendicular density gradient will be established in this case also and the streaming due to $\vec{B} \times \vec{\nabla} U$ will be added in the diurnal vector to give large value than the quiet days value.

4.3.3 Diurnal Anisotropy During The Passage of CME (Cold Magnetic Enhancement) Associated Clouds

In Fig. 4.5(a) the A_p index, diurnal amplitude and its phase have been plotted on upper, middle and lower panels respectively from -5 to +5 days from the zero-day. The zero-day is taken as the arrival day of this category of clouds. From the figure it is clear that the A_p index and diurnal amplitude are higher at zero day in comparison to -1 day and earlier days. These clouds moves with a slower velocity than other two category of clouds(table 4.1). Since the total average duration of these clouds is more than a day, hence the increase in diurnal amplitude on +1 day is also seen in the middle panel of this figure. After the removal of the clouds

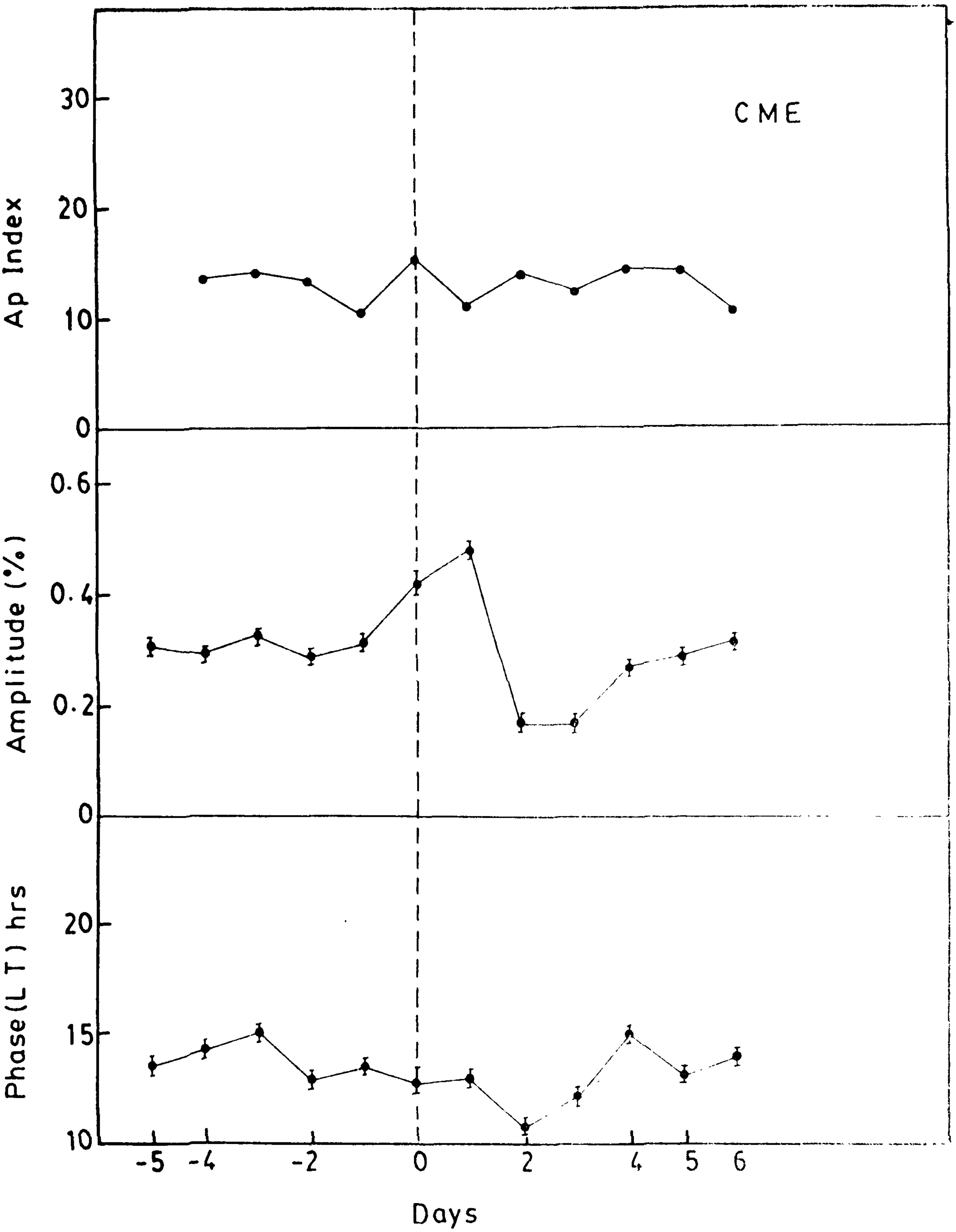


Fig. 4.5(a) Superposed epoch analysis results for $\pm$ 5 days about zero day of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively for cold magnetic enhancement (CME) associated clouds. Zero day is the arrival day of these clouds on the Earth.

from the Earth, the diurnal amplitude returns to its undisturbed (before arrival of the clouds) values with slightly less magnitude of diurnal amplitude and remains nearly at the same level onward (Fig. 4.5 a). The phase shift to earlier hours is clearly seen on the lower panel of this figure. The phase also returns to its undisturbed value after +3 day.

Considering maximum duration of stay of these clouds on the Earth, as zero-day the Fig. 4.5(b) have been plotted with A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days. The features of this figure are similar to the features of Fig. 4.5(a).

Fig. 4.5(c) shows the plotts of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days. The zero-day has been considered the total duration days of this category of clouds. The features of this figure are similar to the features of the fig. 4.5(b). These observations which are discussed above are in close agreement with the theoretical calculations made by Kadokura and Nishida (1986) on two-dimensional numerical modeling of cosmic ray storms.

The direction of the magnetic field of the front boundary of these clouds is northward (-) or toward Sun. (table 4.1). The density gradient perpendicular to the ecliptic will be established as discussed earlier. The field dependent streaming due to $\vec{B} \times \vec{\nabla} U$ will be added in the corotation streaming in such a way that diurnal amplitude will be less than the shock associated clouds which have southward (+) magnetic field. Although this diurnal amplitude is greater than the quiet days amplitude, showing the effect of the genuine disturbance caused by magnetic clouds.

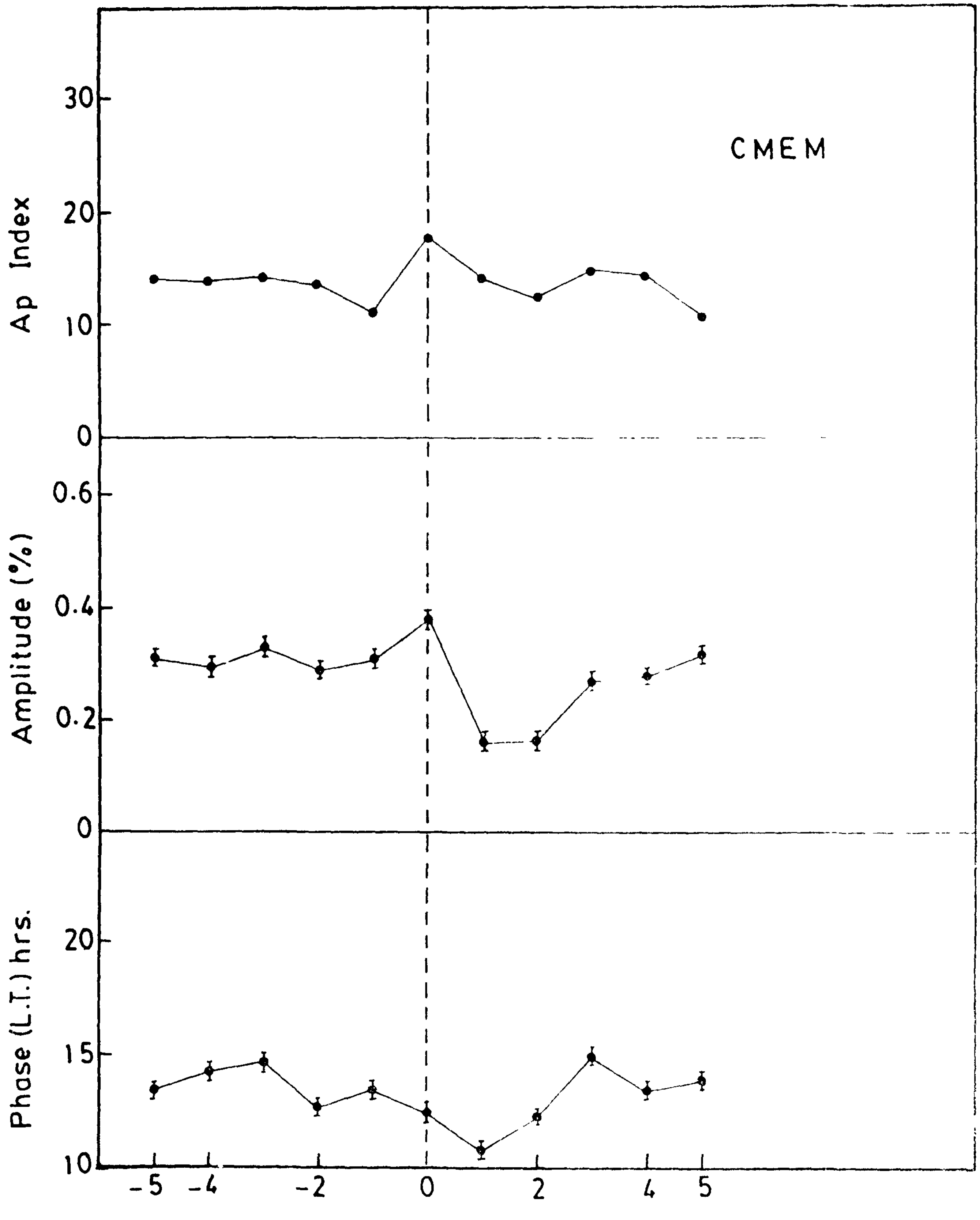


Fig. 4.5 (b) Same as Fig. 4.5(a). Zero day is the maximum duration of stay of these clouds on the Earth. (CMEM).

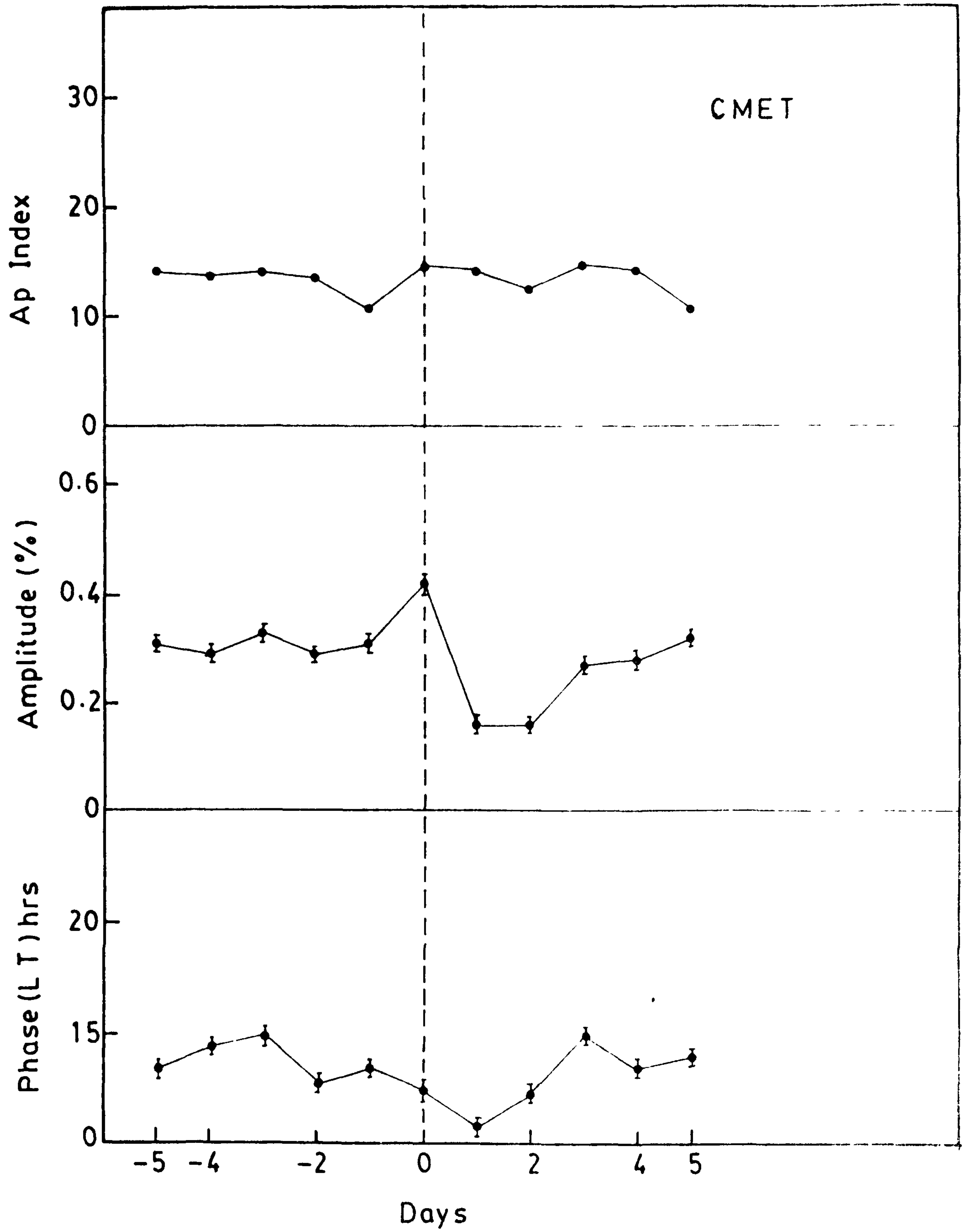


Fig. 4.5(c) Same as Fig. 4.5(a). Zero day is the total duration of stay of these clouds on the Earth (CMET).

4.4 CONCLUSION

From the above discussion we conclude as follows:

1. The amplitude of (i) shock associated clouds (ii) clouds followed by interaction regions and (iii) clouds associated with CME (cold magnetic enhancement) are in descending order i.e. $A_{SAC} > A_{IR} > A_{CME}$ (0.6%, 0.48% and 0.40% at ground).
2. The ratio between the amplitudes $A_{SAC} : A_{IR} : A_{CME}$ is 1.5 : 1.25 : 1 nearly.
3. The phase are 13.1 hr, 13.4 hr and 12.8 hrs local time at Deep River neutron monitor for shocks associated clouds, clouds followed by interaction region and clouds associated with CME (cold magnetic enhancement) respectively.
4. -5 to +5 days analysis shows that roughly in all three categories of clouds the amplitude as well as phase returns to their undisturbed values after the removal of the disturbance caused by clouds in accordance with the recent theoretical calculation on two-dimentional numerical modeling in cosmic ray storms by Kadokura and Nishida (1986) and observations by Wada and Suda (1980) for such type of disturbed periods.
5. Amplitude shows direct relation with geomagnetic index A_p as shown in different figures.
6. The increase and large value of amplitude for shock associated clouds and decrease and small value for the clouds associated with cold magnetic enhancements is in accordance with the contribution due to perpendicular particle density gradient and $\vec{B} \times \vec{\nabla} U$ term.

7. The large values of amplitude and phase shifts can be explained with the help of equation (4) taking all components into consideration.

8. The mechanisms operating and the significance of not neglecting third and fourth terms in equation (4) are given in the discussion part of text.

9. The evidences relating to large perpendicular density gradient and hence contribution from $\vec{B} \times \vec{\nabla} U$ term are summarized in the text in discussion part.

10. The phase shift is towards earlier hours in accordance with the earlier results.

CHAPTER V

DIURNAL ANISOTROPY OF COSMIC RAYS DURING THE PASSAGE OF INTERPLANETARY SHOCKS ON EARTH

5.1 INTRODUCTION

Interplanetary shock signatures are found in the most distant solar wind plasma data (out to $\sim$30 AU). Some of these are expected to be the result of the evolution of 'Corotating' interacting stream structures observed closer to the Sun (Pizzo, 1983). Evidence of proton density and temperature jumps at the times of the abrupt speed increases during periods of continuous data was noted to verify the shock signatures and to enable distinction between forward and reverse shocks (C_f Colburn and Sonett, 1966).

Observations of shock wave disturbances near 1 AU indicate that a significant amount of mass ($\sim 10^{16}$g) is released into the solar wind at the time of major solar disturbances (Hundhausen et.al. 1970). Space-born coronagraph observations of coronal mass ejection events [e.g. Stewart et.al. 1974; Gosling et.al. 1974; Sheeley et.al. 1980] have dramatically confirmed that this is indeed the case. Previous studies of interplanetary shocks have rarely been able to show a direct association between interplanetary shocks and coronal mass ejection events (see, however Gosling et.al. 1975). This is true primarily because most interplanetary observations are made close to the sun-earth line, while white light coronal transients are observed at the solar limb. However, the Helios satellites spent much of 1979-1980 located roughly above the west limb of the Sun. Of the 24 shocks observed by Helios during this interval, 22 could be confidently associated with white light coronal transients observed by orbiting coronagraphs (Sheeley, 1981). Thus there is good reason to suspect that almost all shock wave disturbances at 1 AU are produced by coronal mass ejection events. Plasma observed immediately after shock passage at 1 AU is compressed ambient solar wind. When the observing geometry is favourable, the shocked ambient plasma is followed ($\sim$10-20 hours after shock passage) by the coronal ejecta itself. Often the ejecta can be identified by one or more anomalous solar wind conditions, such as the abundance [A(He)] enhancements (e.g. Hirshberg et.al., 1972), proton temperature depressions (e.g. Gosling et.al., 1973), electron temperature depressions (e.g. Montgomery et.al., 1974), unusual heavy ion ionization states (e.g. Bame et.al. 1979; Fenimore, 1980; Schwenn et.al. 1980; Gosling et.al. 1980), high magnetic field strength (e.g. Hirshberg and Colburn, 1969; Schatten and Schatten 1972; Burlaga and King, 1979), and bidirectional streaming of either energetic protons (e.g. Palmer et.al., 1978)or solar wind electrons (e.g. Temny and Vaisberg, 1979; Bame et.al., 1981).

A He^{++} abundance enhancement is probably the most widely accepted of the above signals of the coronal mass ejecta following shocks and was the first to be recognised in the data (e.g. Gosling et.al. 1967; Bame et.al., 1968; Ogilvie et.al., 1968; Lazarus and Binsake, 1969; Hirshberg et.al., 1971).

Borrini et.al.(1982) has made an analysis of all the interplanetary shock wave disturbances detected with Los Alamos plasma instruments aboard IMP 6,7 and 8 from 1971 to 1978. The study of the 103 foward shocks observed reveals that shocks occur preferentially during conditions of low proton temperature and speed and that the shell of shocked gas followed shock passage is typically ~0.14 AU thick. Helium enrichments (Helium/hydrogen flux ratio $\geq$ 8%) are observed in association with 46% of the shocks. Shocks followed by helium enrichments (He shocks) are on the average the strongest shocks observed, in the sense that they exhibit the largest jumps in flow speeds, temperature and magnetic field strength and induce the largest geomagnetic response. The geometry of sampling the disturbances may account for the difference between He and non-He shocks. There is a tendency for interplanetary shocks and helium enrichments to be part of complex, multiple events. This may result from multiple out bursts from the same solar active region. Usually the helium enrichment is found in plasma of higher than average field strength.

Because of dynamic character of the mechanisms that produce transient fluctuations in the cosmic ray intensity it is exceedingly difficult to comprehened them in any detail. It is clear that observed properties of Forbush decreases are attributable to specific features of the interplanetary magnetic field which may occur individually or in combination. These include (1) magnetic irregularities: rapid or slow fluctuations in the direction or magnitude of the IMF. (2) magnetic bottles or tongues: extended structures of intense magnetic field; and (3) shocks or blast waves and tangential discontinuties.

The phenomena in group 1 above are in the convection - diffusion approximation of the transport equation that describes the streaming of the cosmic rays in the interplanetary medium. Some of the observed transient intensity variations can be ascribed to rapid changes in the parameters that determine the net anisotropy or modulation. Both group 2 and group 3 above are manifestations of the motion of boundaries, and, in effect, the relevent theoretical analysis describes the sweeping up of particles by a moving semipermeable membrane. Combinations of these departures from equilibrium conditions undoubtedly play a role in many of the observed transitory modulations and anisotropies.

The cosmic ray modulation has been known to have various time scales. The 11-year modulation corresponds to the solar activity cycle, the 27-day recurrent madulation reflects the solar rotation, and the 1-day anisotropy is related to the Earths rotation. A cosmic ray storm, which has traditionally been referred to as a Forbush decrease (FD), is a short term modulation that results from the solar activity. It often starts within about one hour of a geomagnetic storm sudden commencement (SSC), and this suggests that the cause of the FD is the interplanetary shock wave produced by solar flares or corotational streams.

The role of the solar wind in the cosmic ray modulation has been called 'convection'. The irregularities of the magnetic field which represent scattering centres are transported outward by the solar wind and act to resist the entry of cosmic rays. Thus the enhancement of the solar wind velocity means the intensification of this driving-out effect and is expected to lead to the intensity depression.

The enhancement in the magnetic field behind the shock coresponds to the increase of the angle between the magnetic field line and the radial direction. Because cosmic ray particles move along field lines more easily than across it, the increase in the angle means the reduction of the radial flux and intensity depression.

The enhancement in the variability of the IMF would correspond to the enhancement in the degree of the scattering by magnetic irregularities, decrease in the diffusion coefficient along the field line, (Suda et.al. 1981) and hence the intensity depression of cosmic rays.

The other condidate for the cause of the FD have also been pointed out. Barouch and Burlaga (1975, 1976) suggested the importance of the gradient $\vec{B}$ drift at the shock front and Thomas and Gall (1984) suggested by numerical calculation that the main cause of the FD was the adiabatic cooling behind the shock. Recently, Badruddin et.al. (1986) showed that shock associated clouds produce Forbush decreases.

At the time of the FD the anisotropy also changes. According to Wada and Suda (1980) the amplitude of the solar diurnal anisotropy increases and the phase advances to the earlier hours. The north-south anisotropy is also enhanced and its direction is consistent with that of the density gradient drift (Suda et.al. 1981). It is well known that the anisotropy perpendicular to the ecliptic plane is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971, 1976; Mercer et.al. 1971). The sense of the north-south anisotropy varies from event to event. Infact, during a single Forbush decrease the sign can change several times (Duggal and Pomerantz; 1971).

A particle drift proportional to $\vec{B} \times \vec{\nabla} U$ is produced by the cosmic ray density gradient $\vec{\nabla} U$ in the presence of the interplanetary magnetic field $\vec{B}$. Since $\vec{B}$ is considered in the ecliptic plane, the north-south component of $\vec{\nabla} U$ produces a flow in the ecliptic plane perpendicular to $\vec{B}$ whose sense depends on the sense of $\vec{B}$. This will be observed as field dependent vector addition to the usual azimuthal streaming. This effect may be detected by separating the diurnal variation vectors into groups corresponding to positive and negative fields (Hashim and Bercovitch, 1972; Swinson, 1970).

In this Chapter we will study the behaviour of diurnal anisotropy during the days in which interplanetary shocks are observed at the Earth. These interplanetary shocks are identified by Borrini et.al. (1982) as discussed in the beginning of the introduction. These shocks cover a period from 1971 to 1978. The Forbush decreases are associated with these shocks. Hence our interest is to study the diurnal variation under the disturbed conditions produced by interplanetary shocks.

5.2 METHOD OF ANALYSIS

The hourly interval of the passage at the Earth of 44 He- shocks and 47 non- He shocks have been taken as the key-hour for the superposed epoch analysis using the pressure corrected hourly counting rate of Deep River neutron monitor in order to see the effects of these shocks on the cosmic ray intensity.

A superposed epoch analysis has also been performed to calculate the diurnal amplitude and phase by using the day of passage of interplanetary shocks as key-day. The $\pm$ 5 day window about the key-day allows a thorough characterisation of preshock and post shock flow conditions. These interplanetary shocks have been splitted into the events according to whether or not a helium abundance enhancement followed the shocks i.e. these have been divided into helium and non-helium shocks.

Then helium shocks have been splitted into two groups again according to the IMF polarity of the key-day and the same procedure as above was followed. The non-helium shocks have also been analysed in the same manner as helium shocks. Thus average behaviour of the interplanetary shocks affecting the diurnal amplitude and phase has been studied.

Since the simple harmonic analysis teachnique cannot be applied because mostly shocks produce Forbush decreases. Hence the technique which separates Forbush decreases and diurnal variations has been used to calculate the diurnal amplitude and phase. This technique has been discussed in detail in Chapter number II.

5.3 RESULTS AND DISCUSSION

The result of our superposed epoch analysis for He-shocks is shown in Fig. 5.1. It shows a classical Forbush decrease ($\sim$2.0%) setting in at the shock time, a sharp decrease upto $\sim$15 hours (approximate duration of the passage of shocked plasma may be considered to be 12 - 18 hours), then this decrease continuing (though rather slowly) upto 42 hours (the average duration of piston plasma cloud behind the shocked plasma is $\sim$20 - 30 hours) and then the recovery starts which is complete in a week time. The decrease observed in cosmic ray intensity in association with non - He shocks (Fig. 5.2) is comparatively very small ($\sim$0.6%), setting at shock time, starts recovering just after $\sim$20 hours and reaches a almost constant level in only two days. Both the superposition results do not show any preincrease. A similar epoch analysis has been presented earlier by Ankiewicz et.al. (1983) by considering all the 103 shocks together. Their result show a decrease ($\sim$1.4%) setting at shock time.

A Forbush decrease is a transient (non-periodic) cosmic ray modulation that results from shock disturbances as is clear from Figs. 5.1 and 5.2. The investigation of Forbush decreases would also lead to the understanding of the modulation with other time scales. In one of our recent papers (Badruddin et.al. 1986) we have expressed the view that the turbulence behind the shock front is most likely additional effect in producing Forbush decreases. The current status of knowledge of these Forbush decreases can be summarized as follows:

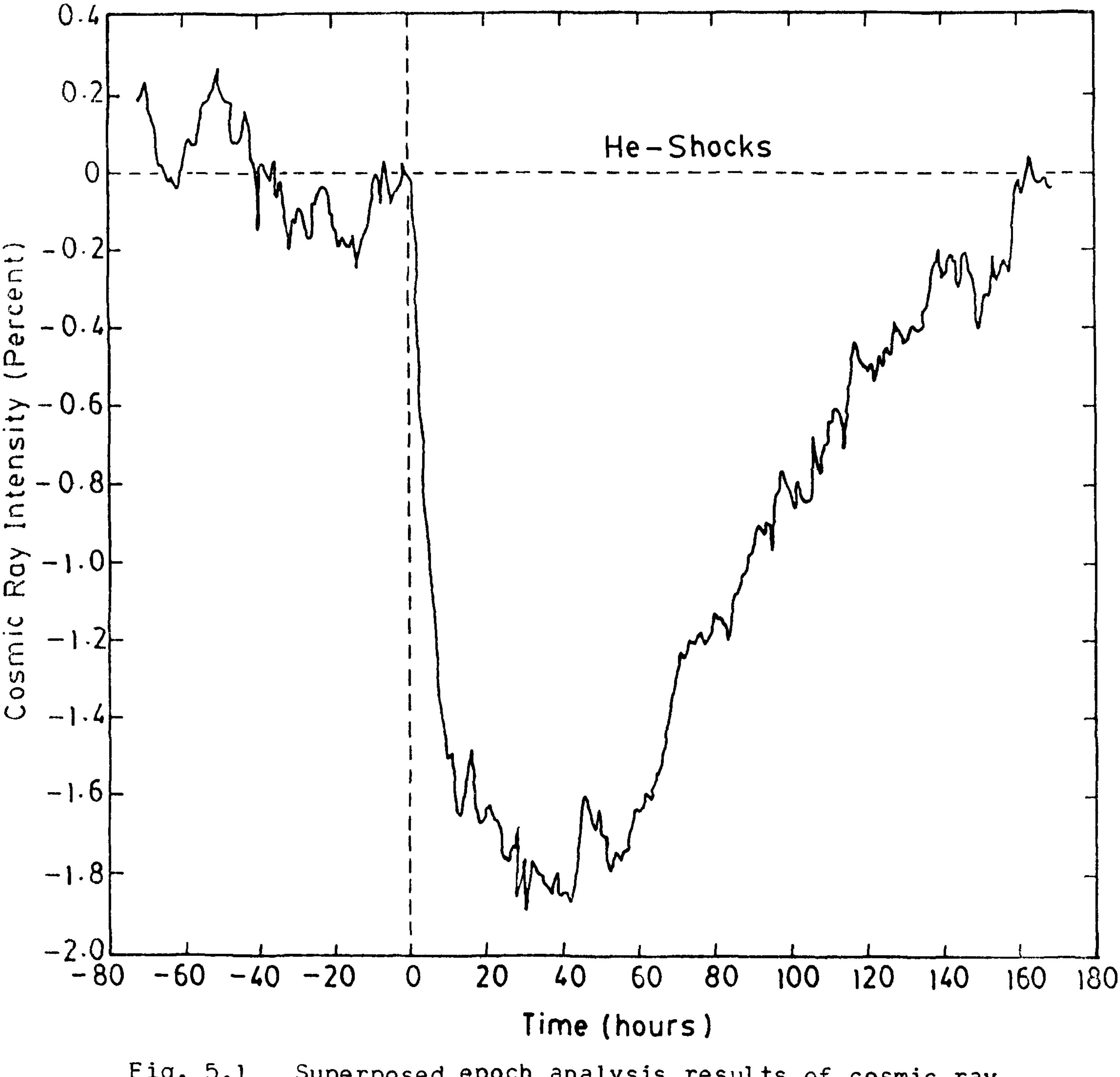


Fig. 5.1 Superposed epoch analysis results of cosmic ray intensity reduction with zero epoch of arrival hour on the Earth for interplanetary He- shock.

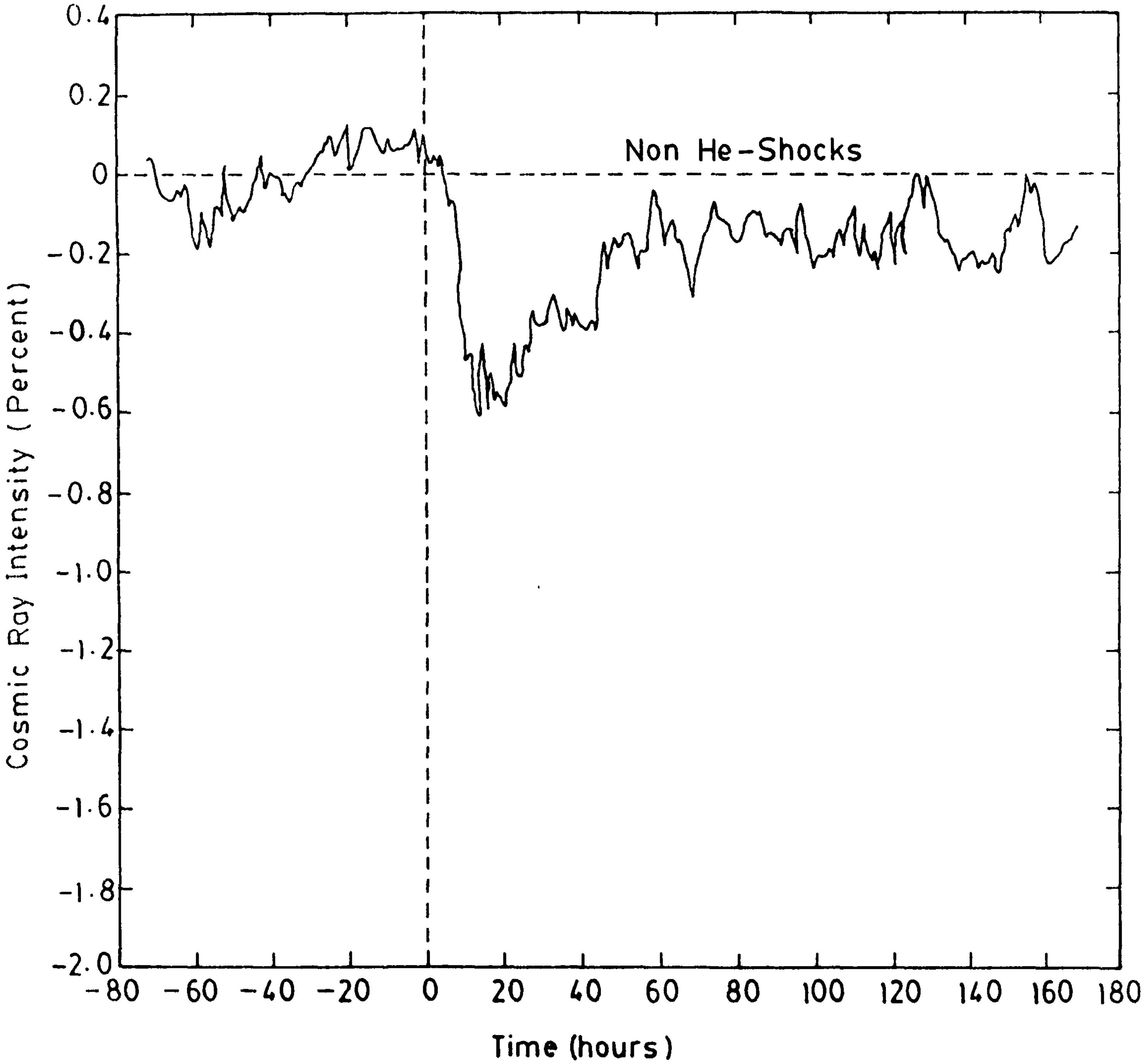


Fig. 5.2 Same as Fig. 5.1 for interplanetary non He- shocks.

(i) enhancement in the interplanetary magnetic field magnitude (magnetic blobs or clouds) and large variability in the field direction are generally observed in the initial phase of the FDs;

(ii) in most cases the magnetic blob or cloud is accompained by a flare - generated shock which is often followed by a flare ejecta piston or driver gas;

(iii) a fast solar wind stream is observed during most of FDs.

Fig. 5.3 shows the diurnal amplitudes and phases for helium abundance enhancement associated shocks (i.e. He - shocks) and non-He shocks on the harmonic dial. It is clear from the figure that diurnal amplitude for He - shocks is larger than non - He-shocks. He - shocks are strongest shocks than non - He shocks as shown by Borrini et.al. (1982). This has also been proved through our analysis as the diurnal amplitude is larger for He- shocks than non - He-shocks. The diurnal phase shift, towards earlier hours in both cases, is in accordance with the general trend when any disturbance arrives on the Earth (table 5.1).

Fig. 5.4 shows the diurnal amplitudes and phases for He- shocks on the harmonic dial when these shocks are splitted into two groups according to the IMF polarity on key-days i.e. key days have been selected according to away (+) and toward (-) polarity days. For comparison the diurnal amplitude and

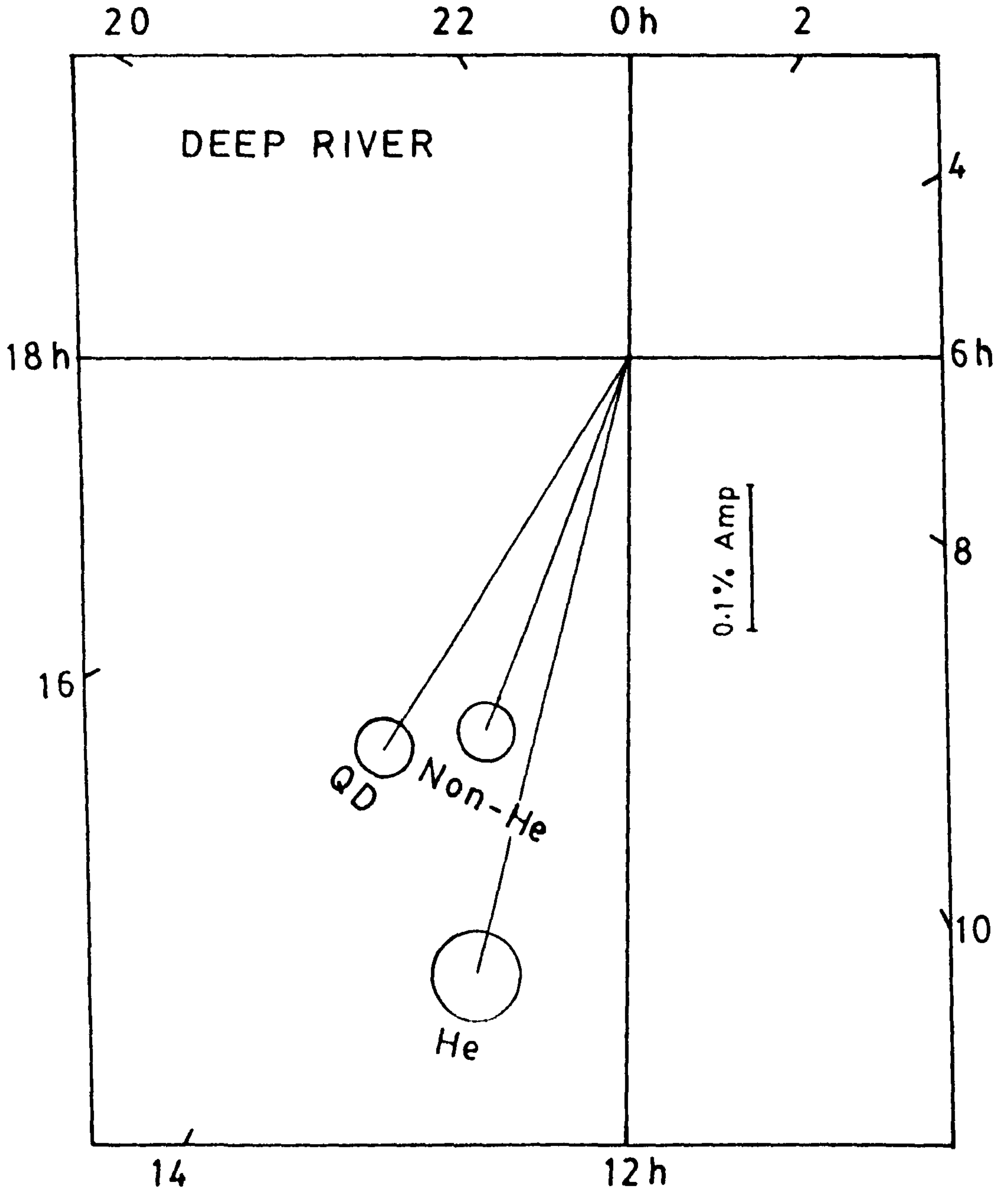


Fig. 5.3 Diurnal amplitude and phase on harmonic dial for two types of interplanetary shocks. Key day is the arrival day of the shocks.
He : Helium enhancement associated shocks
Non-He: Non-Helium enhancement associated shocks
QD : Quiet days

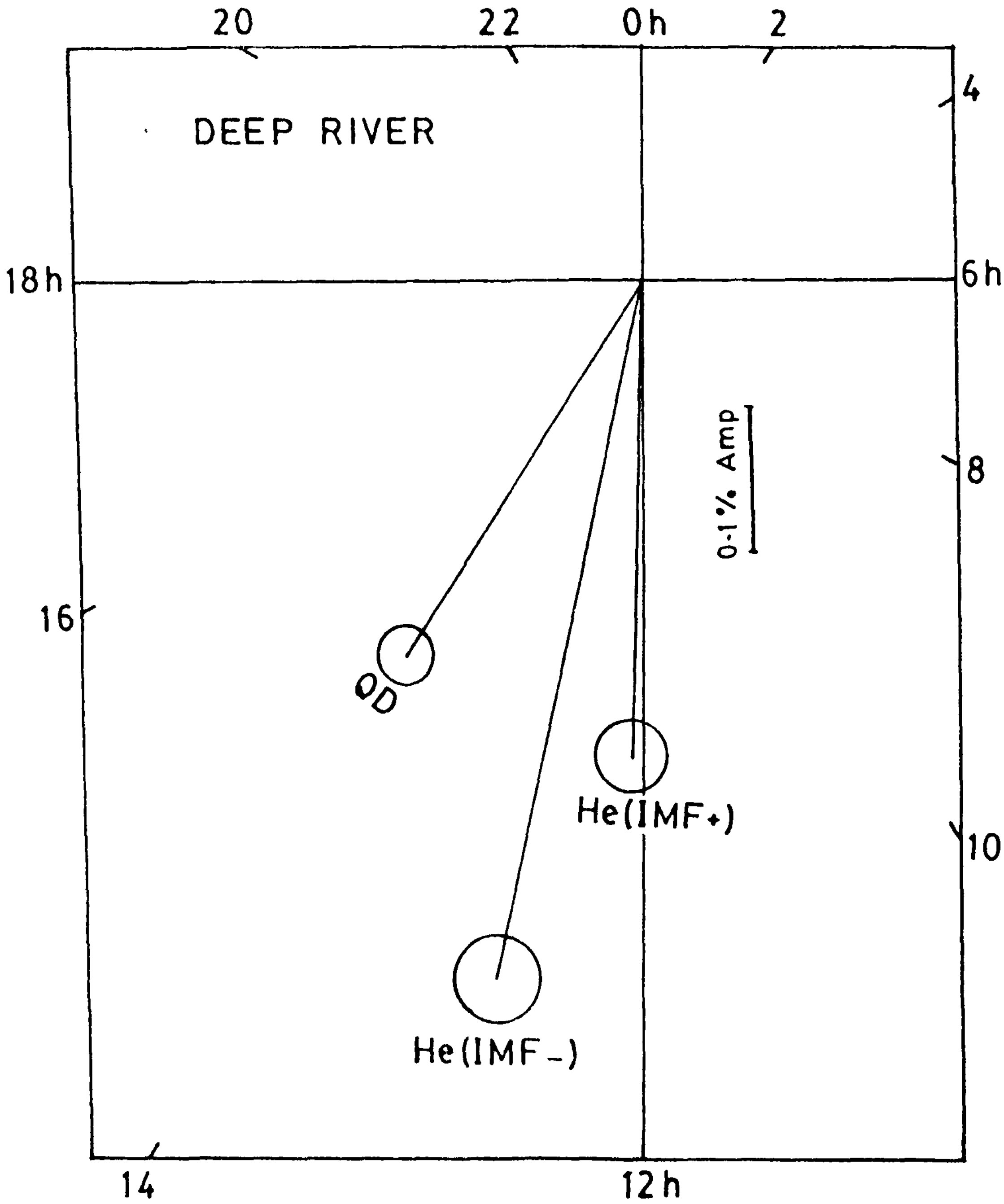


Fig. 5.4 Same as Fig. 5.3 for the He-shocks with IMF polarity away (+) and toward (-) on key-day which is the arrival day of these shocks.

Table 5.1 Diurnal amplitude and phase during the passage of Interplanetary shocks at Deep River

Type of shocks	Key day arrival day of shocks		Key day when IMF southward(+)		Key day when IMF northward (-)	
	Amplitude(%)	Phase (LT) hours	Amplitude(%)	Phase (LT) hours	Amplitude(%)	Phase(LT)hours
He- Shocks	0.44 ± 0.03	12.89 ± 0.12	0.34 ± 0.02	12.1 ± 0.12	0.51 ± 0.03	12.8 ± 0.12
Non-He shocks	0.28 ± 0.01	13.4 ± 0.14	0.34 ± 0.02	13.4 ± 0.14	0.24 ± 0.01	13.3 ± 0.13
Quiet days	0.32 ± 0.02	14.25± 0.15				

phase of magnetically quiet days for the period 1971 to 1978 is also shown on the same harmonic dial. Here the diurnal amplitude for toward (-) polarity days on key day is larger than away polarity days (table 5.1). In these shocks the driver gas also possesses the strong compressed magnetic field. It seems that in this case the direction of the magnetic field in the driver gas (ejecta) is dominating. The diurnal amplitude is largest and is similar to the shock associated clouds which have southward (+) magnetic field in their front boundary as discussed in the previous Chapter number IV. Pudoukin et.al. (1977) in his paper on the structure of the solar flare stream magnetic field showed thatsome pecularities of the structure of the flare stream magnetic field seem to depend on the relative orientation of the magnetic field within the main body of the stream and within the background solar wind. They also showed that the southward (+) magnetic field of the main body of the stream dominate. Hence it seems that the orientation of the magnetic field of these shocks would have been southward (+) and dominated on the ambient solar wind magnetic field i.e. IMF. The diurnal amplitude for IMF (+) polarity days is not much larger than the diurnal amplitude of quiet days. There is clearcut phase shift towards earlier hours in both cases as is seen from this figure.

Fig. 5.5 shows the diurnal amplitudes and phases of non He-shocks when these are splitted into away (+) and toward (-) polarity days of IMF on the key-day. The difference between the diurnal amplitudes for away (+) and toward (-)

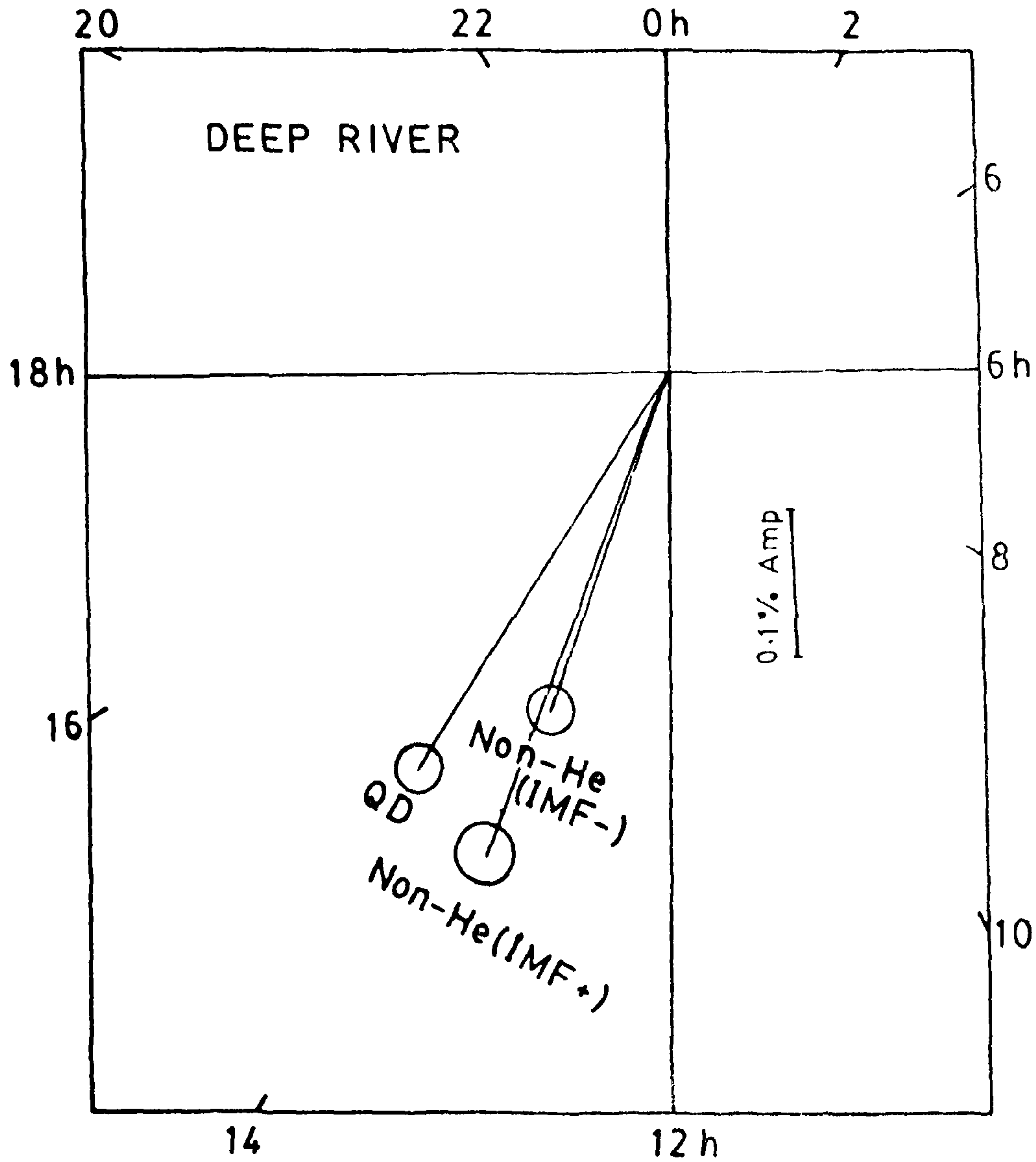


Fig. 5.5 Same as Fig. 5.3 for non He- shocks with IMF polarity away (+) and toward (-) on key-day which is the arrival day of these shocks.

polarity days is significant and the phase shift, towards earlier hours in comparison to the quiet days phase, is seen from this figure. Since these shocks donot possess ejecta behind them, hence the ambient solar wind magnetic field (IMF) will be compressed and its direction will be responsible for the diurnal amplitude. The average velocity of these shocks on key-day is in the declining phase (Borrini et.al. 1982). Murayama (1975) and Iucci et.al. (1983) showed that thediurnal amplitude, in the declining phase of velocity, is reduced then the normal value; hence our results are in accordance with the results of above authors on the key-days of these shocks where the velocity profile is in the declining phase.

Fig. 5.6 shows the behaviour of He- shocks with a ± 5 days window about the key-day as the arrival day of the shocks on the Earth. In this figure preshock behaviour related to diurnal amplitude and phase is apparent. On the key-day the diurnal amplitude increase is large. The driver gas follows the shocks within 48 hours of the passage of the shocks. The effect of this ejecta is seen upto ± 2 day from the key-day. After that the diurnal amplitude and phase returns to its preshock values. This result is in agreement with the theoretical calculations of Kadokura and Nishida (1986) on two-dimensional numerical modeling of cosmic ray storms. These authors have shown that when solar wind disturbance is passed the diurnal amplitude and phase returns to its predisturbance values.

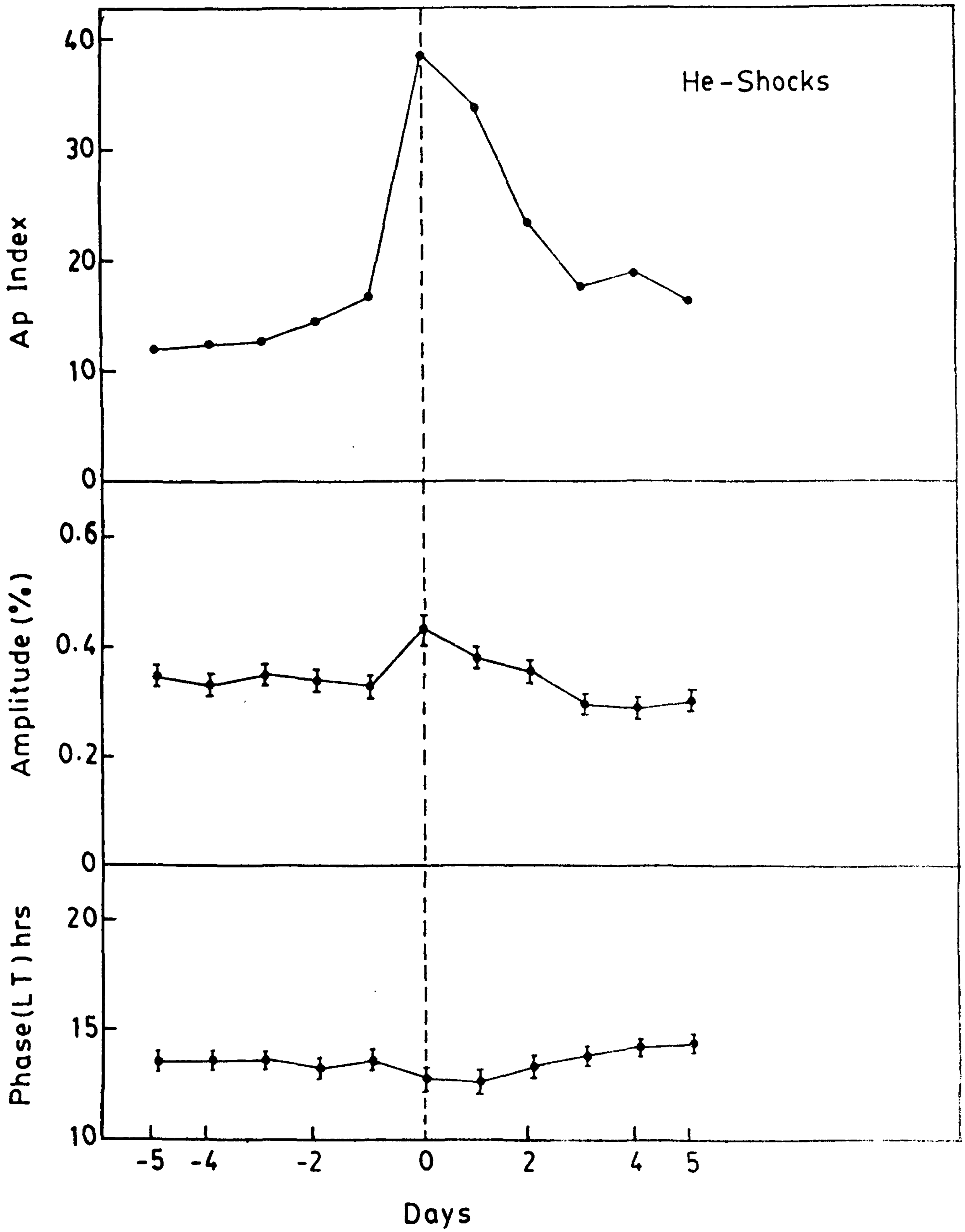


Fig. 5.6 Superposed epoch analysis results for ± 5 days about key-day of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively for He- shocks. Key-day is the arrival day of these shocks.

Fig. 5.7 (a) shows the preshocked and postshocked behaviour for He- shocks for away (+) polarity days as key-day. The diurnal amplitude is large on key day and +1 day and phase shifts towards earlier hours. After the removal of the solar wind disturbance i.e. after +2 day the diurnal amplitude and phase returns to almost their values before the arrival of the disturbance.

Fig. 5.7 (b) shows the behaviour for toward (-) IMF polarity days as the key-day. The large value of diurnal amplitude on key-day in comparison to the away (+) polarity days is explained with the fig. 5.4. The A_p index is largest on the key-day. The remaining features are as in Fig. 5.7(a).

Fig. 5.8 shows the preshocked and post shocked behaviour of non He-shocks with a ±5 days window about the key-day as the arrival day of these shocks on the Earth. In this figure A_p index is increased while the diurnal amplitude does not increase on key-day as these days fall on the declining phase of solar wind velocity (Murayama, 1975; Iucci et.al. 1983). There is a jump in the average velocity of these shocks within 12 hours of their arrival and another jump after 12 hours with the enhancement in magnetic field (Borrini et.al. 1982). Hence the effect of these parameters on the diurnal amplitude is seen upto +2 day. Thereafter the diurnal amplitude and phase return to their pre-shocked values. The phase also shifts slightly towards earlier hours and recovers after +2 day to its preshocked value.

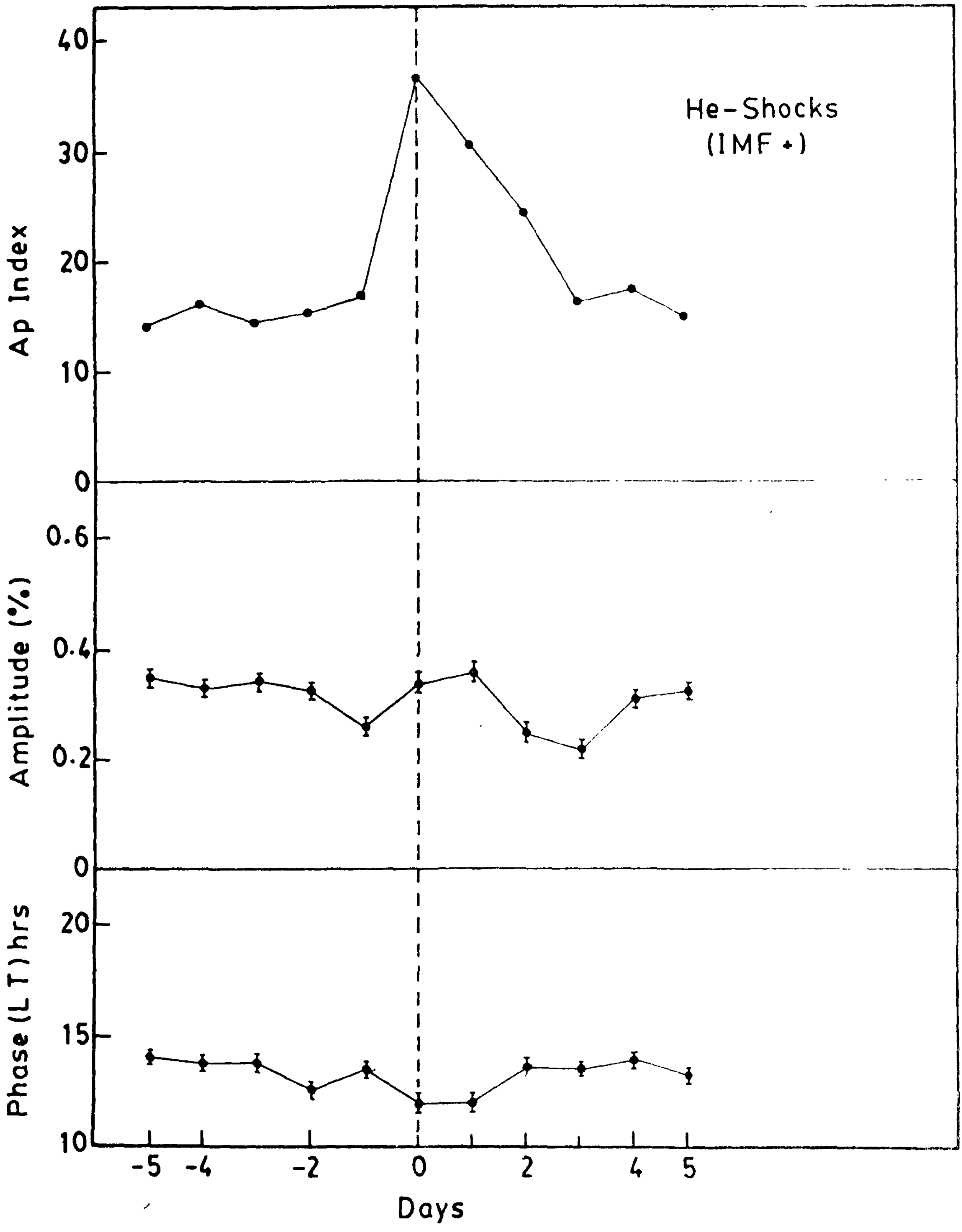


Fig. 5.7 (a) Same as Fig. 5.6 for He- shocks with IMF polarity away (+) on the key-day which is the arrival day of these shocks.

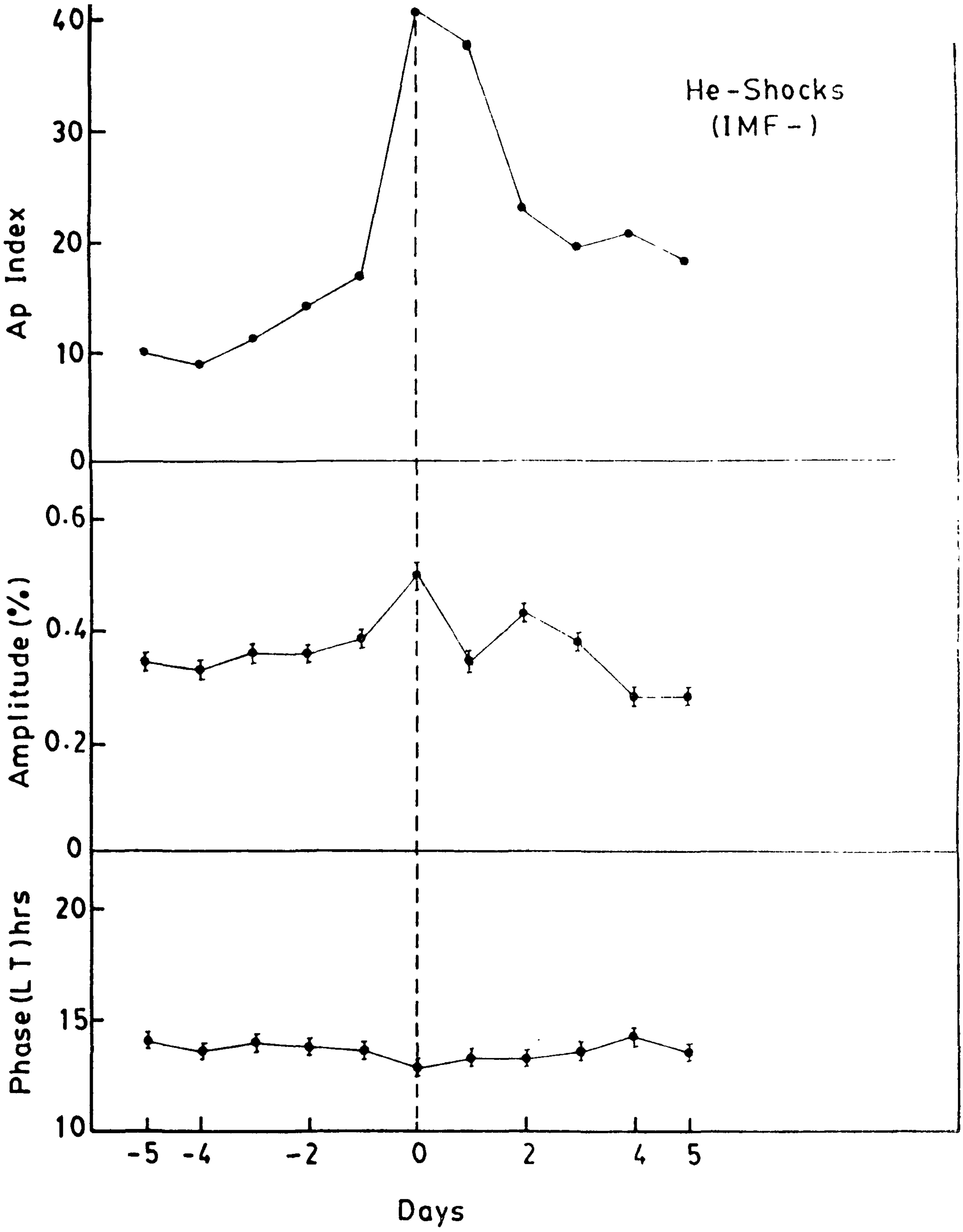


Fig. 5.7 (b) Same as Fig. 5.6 for He-shocks with IMF polarity toward (-) on the key-day which is arrival day of these shocks.

Fig. 5.9 (a) shows the preshocked and post shocked behaviour for away (+) polarity days on key day. The diurnal amplitude increases on key day and remain increased upto +2 days. Thereafter it returns to its preshocked value. Phase also shifts towards earlier hours and recovers after +2 day.

Fig. 5.9 (b) shows the behaviour on both sides of key-day which have been taken as the toward (-) polarity days. A_p index increases diurnal amplitude decreases on key-day. The decrease of diurnal amplitude on key day confers the effect of polarity (-) and declining phase of velocity. On +1 day diurnal amplitude increases which shows that there is a sudden jump in the velocity profile and enhancement in the magnitude of magnetic field as shown by Borrini et.al. (1982). Diurnal phase also shifts slightly towards earlier hours and recovers after +2 day.

The most general expression for the theoretical cosmic ray anisotropy is given in terms of Fokker – Planck formalism (Jokipii and Parker, 1970, Forman and Gleeson, 1975).

$$\vec{\delta} = \frac{3\vec{S}}{vU} = 3C_G\vec{V}_w/v - \vec{K}\cdot\vec{\nabla}U$$

Here

$\vec{S}$ = differential cosmic ray current density

U = the differential cosmic ray density

$\vec{K}$ = cosmic ray diffusion tensor [Forman and Glesson 1975]

C_G = Compton - Geeting factor (Glesson and Axford 1968]

= $(2 + \alpha\gamma)/3$

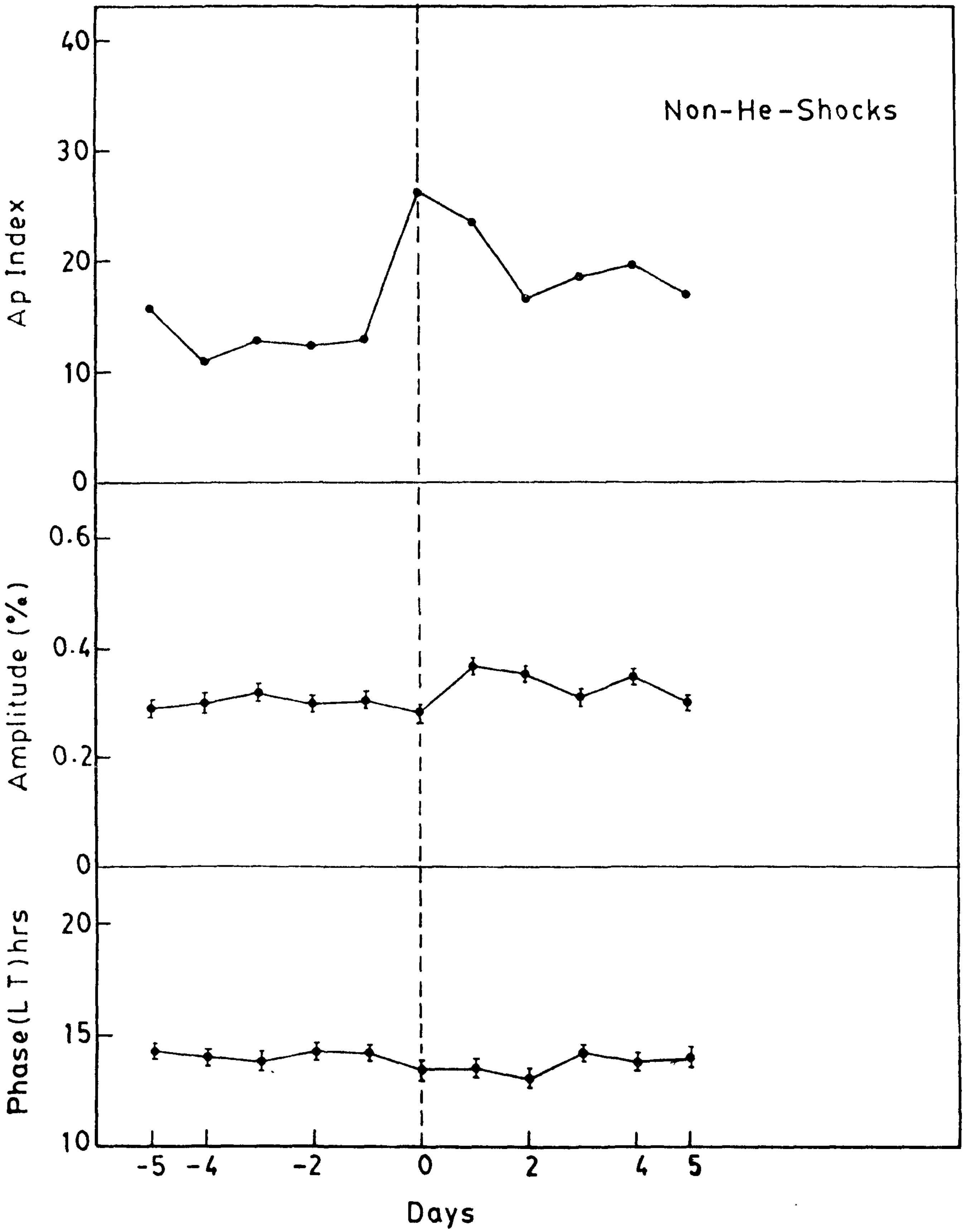


Fig.5.8 Superposed epoch analysis results for ± 5 days about key-day of A_p index, diurnal amplitude and phase on upper, middle and lower panels respectively for non He- shocks. Key-day is the arrival day of these shocks.

where

α = $(T + 2m_oC^2)/(T + m_oC^2) \backsim 1$ for these energy particles (GeV)

γ = cosmic ray differential intensity spectral index ($\backsim 2.5$)

$\vec{V}_w$ = Solar wind speed

v = particle velocity

The parameters associated with the diurnal anisotropy are the cosmic ray gradients, the solar wind speed, the mean inter-planetary magnetic field direction and the coefficients for the cosmic ray diffusion.

As has been discussed in detail in Chapter number IV of the thesis, the most convenient form of anisotropy vector can be given as follows:

$$\vec{\xi} = \vec{\xi}_c - \frac{3K_{||}}{v}\vec{G}_{||} - \frac{3K_{\perp}}{v}G_{\perp} - \frac{\omega\tau}{1+(\omega\tau)^2}\rho\vec{G} \times \frac{\vec{B}}{B} \qquad \dots\dots 4.4$$

or

$$\vec{\xi} = \vec{\xi}_c + \vec{\xi}_{||} + \vec{\xi}_{\perp} + \vec{\xi}_G \qquad \dots\dots 4.5$$

The successive terms are due to convection (directed radially outward), parallel diffusion, perpendicular diffusion and the density gradient current. As discussed in the Chapter IV the

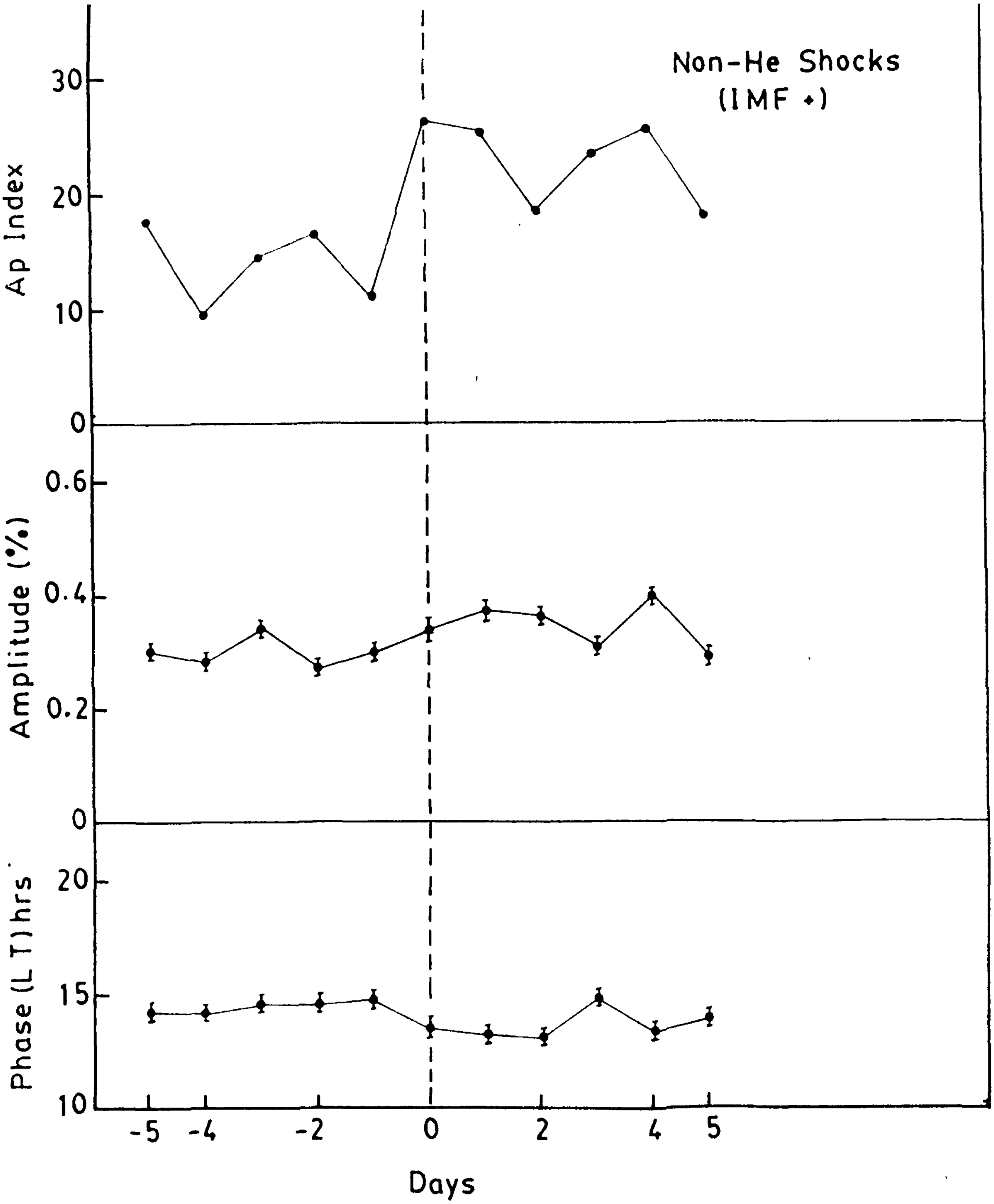


Fig. 5.9 (a) Same as Fig. 5.8 for non He- shocks with IMF polarity away (+) on the key-day which is arrival day of these shocks.

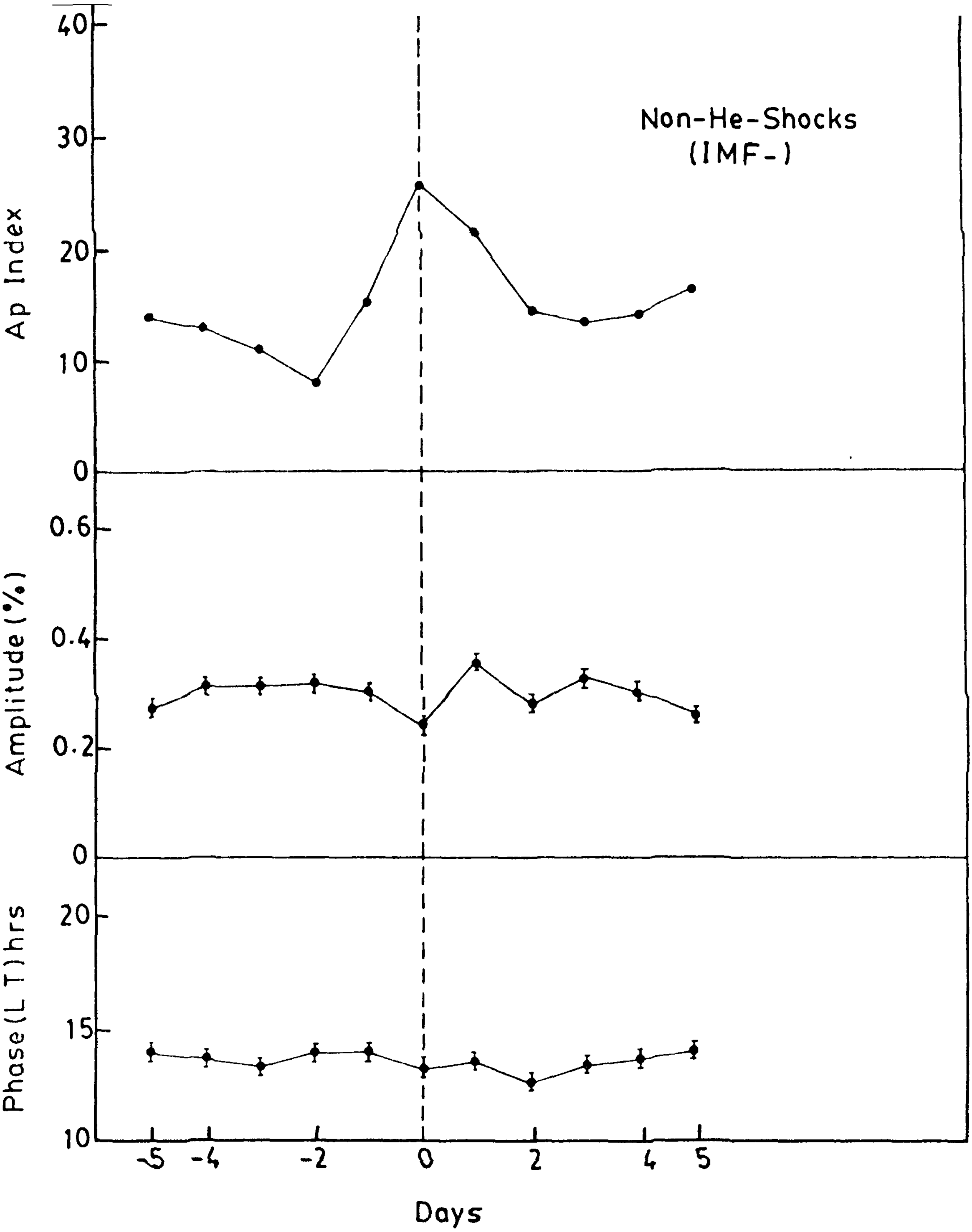


Fig. 5.9 (b) Same as Fig. 5.8 for non He- shocks with IMF polarity toward (-) on the key-day which is arrival day of these shocks.

last two terms of equation 4.5 i.e. $\vec{\xi}_{\perp}$ and $\vec{\xi}_{G}$ can not be neglected. They should be considered because Forbush decreases are associated with the interplanetary shocks (Fig. 5.1 and 5.2) and the cosmic ray particle density gradients perpendicular to the ecliptic plane are established which are 10 - 20 times the quiet time gradients (Yoshida et.al., 1973).

As the piston plasma of these shocks advances, the drift velocity, which is much larger than the velocity of the piston plasma, is produced due to the large gradient of magnetic field (grade - B of the order of 100 γ/AU (Chapter IV)). This drift velocity is perpendicular to the ecliptic plane. The flow due to $\vec{B} \times \vec{\nabla} U$ (where $\vec{B}$ is magnetic field and lies in the plane of ecliptic and $\vec{\nabla} U$ is the density gradient perpendicular to the ecliptic plane) is superposed on the so-called corotation streaming. Being dependent on the IMF polarity which is toward or away the transport by the particle density gradient drift should bring cosmic rays towards the ecliptic plane.

Some indications of non-field aligned diffusion associated with the variability of the ecliptic magnetic field direction (Ananth et.al. 1973, 1974; Kane, 1975) as well as that associated with reasonably constant ecliptic field directions (Kane, 1975) exist. However, the theoretical relationship between cosmic ray diffusion perpendicular to the mean field and the magnetic field fluctuations is complex and depends on field fluctuations both in and normal to the ecliptic plane. Gradients perpendicular to the ecliptic are observed for short periods in association with disturbed interplanetary conditions (Duggal and Pomerantz, 1976).

In the early investigations of large Forbush decreases noticeable increases in the amplitudes of the daily variation during and after the decrease (Dorman, 1963) were observed. In larger cosmic ray storms, the time of maximum for the daily variation shifted toward earlier hours irrespective of the intensity of the storm. Usually the amplitude of the daily variation was largest during the recovery portion of the Forbush decrease. Venkatesan and Mathews (1968) found the enhanced daily variation during a cosmic ray storm. In this case there was no large Fd recorded at the Earth. The enhanced daily variation probably indicates a disturbance in the normal cosmic ray flow pattern at large distances from the Earth without the modulating region itself engulfuig the Earth (Lockwood, 1968).

Very large anisotropies were also observed following the Fd (Mercer and Wilson, 1968). Changes in both the direction and magnitude of the anisotropy with the maximum intensity of the cosmic-ray flux west of the Earth-Sun line were observed, quite in contrast to that seen in the normal daily variation and in the initial phases of a Fd. Tanskanen (1968) in a very detailed analysis studied the intensity variations for a series of Fds in 1965-1966. It was concluded that during the beginning of the Fd the phase of the first harmonic shifts in the daily variation toward the Earth-Sun direction, occasionally even becomes directed west of Earth-Sun (ES) line. The amplitude becomes several times the predecrease level and this enhanced level may continue for several days. The phase generally returns after a few days to be close to 90° E of the ES line but, in some cases, may go through a period of almost zero amplitude.

Hashim and Thambyahpillai (1969) observed the large amplitude of the daily wave which was attributed to an intensity depression from a limited cone of direction, the axis of which is 45° W of the ES line, McCracken (1962 b) was the first to propose a mechanism for such decreases. Since the stations viewing 45° W of ES line are connected by the interplanetary field to a region of depleted cosmic ray intensity lying behind the shock front, the intensity recorded would be decreased. The size of the cone of directions of reduced intensity is related to the scattering by which particles can escape from the modulating region before arriving at the Earth. Hashim and Thambyahpillai (1969) evoke essentially the same mechanism to account for the large variations observed.

The depletion of cosmic ray flux in the garden-hose direction can be related to a possible connection of the Earth with regions of depleted cosmic ray intensity behind the rear end of a shock front which may or may not have produced a Forbush decrease at the Earth depending upon the position of the shock front with respect to the Earth. Where the shock front do produce a Forbush decrease in the high energy cosmic radiation, large anisotropies along the garden hose direction (Fentan et.al. 1959) have been commonly observed. Corotating type of Fd observed at very low energies ($\sim$10 MeV) caused by recurrent active regions are known to often cause only an enhanced diurnal amplitude at high energies (McCracken et.al., 1966).

Enhanced diurnal variation due to an excess flux coming from the ~21 hour direction (Rao et.al. 1971 b) is often observed during the later part of a Forbush decrease indicating the existence of a source in the antigarden hose direction. Such a source can be caused by a positive density gradient following a strong convective removal of particles. Thus during the later part of the diurnal wave train, the anisotropy could be due to an excess flux from the antigarden hose direction. The establishment of such a positive density gradient at low energies (10-50 MeV) during late times in the decay of flare events (McCracken et.al. 1971; Rao et.al. 1971 a) adds strength to the basic concept proposed.

Murayama (1975) analysing some high speed streams occuring during 1967, found that the amplitude of the diurnal wave tends to be smaller in the declining velocity portion of the stream. The author interprets this result by claiming a cosmic-ray diffusion perpendicular to the field lines on the ecliptic plane only in the declining velocity portion of the stream, in which a cosmic ray density rarefaction due to longitudinal velocity gradient could exist. In the declining - speed period of the stream the amplitude of the first harmonic is strongly reduced (Iucci et.al., 1983).

5.4 CONCLUSIONS

The following conclusions can be drawn from the above results and discussion:

1. The diurnal amplitude for He- shocks on the arrival day

is large than the amplitude of non He- shocks.

2. The diurnal phase shifts towards earlier hours in both cases.

3. A pecular behaviour of He- shocks on the arrival day, when the IMF polarity of these days is northward (-), is seen from our results contrary to the results when the IMF polarity of arrival day was southward (+).

4. The diurnal amplitude for northward (-) IMF, on the arrival day is similar to the results obtained for shock - associated clouds which have southward (+) magnetic field in their front boundary as is discussed in Chapter number IV.

5. Hence it seems that the orientation of the magnetic field of these He - shocks, for IMF (-) on the arrival day, is southward (+).

6. It also seems that this southward (+) magnetic field, on the arrival day of these He- shocks, dominates.

7. The effect of southward (+) and northward (-) magnetic field is clearly visible in the case of non- He shocks.

8. The decrease in diurnal amplitude of non- He shocks on the arrival day is due to the declining phase of velocity under which diurnal amplitude reduces as explained previsouly.

9. The values of diurnal amplitudes and phases in different conditions are given in table 5.1.

10. The preshocked and post shocked behaviour are shown in different figures.

11. The contribution of $\vec{B} \times \vec{\nabla} U$ term is significant. This streaming is superimposed on the corotation streaming depending upon the sense of $\vec{B}$.

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INFLUENCE OF MAGNETIC CLOUDS ON COSMIC RAY INTENSITY VARIATION

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Abstract. The data from a high counting rate neutron monitor has been analysed to study the nature of galactic cosmic-ray transient modulation associated with three classes of magnetic clouds, i.e., clouds associated with shock, stream interface and cold magnetic enhancement.

It is found that the decreases in cosmic-ray intensity which are associated with clouds preceded by a shock, are very high (Forbush-type) and these decreases start earlier than the arrival of the cloud at the Earth. From the study of the time profile of these decreases it is found that the onset time of a Forbush-type decrease produced by a shock-associated cloud starts nearly at the time of arrival of the shock front at the Earth and the recovery is almost complete within a week.

The decreases in cosmic-ray intensity associated with clouds followed by a stream interface are smaller in magnitude and larger in duration. The depression starts on the day of the arrival of the cloud.

The decreases associated with the third category of clouds, i.e., clouds associated with cold magnetic enhancement (a region in which plasma temperature is anomalously low and the magnetic field strength is enhanced) are of still smaller amplitude and duration. The decrease in this case starts on the day the cloud arrives at the Earth.

It seems that the Forbush decrease modulating region consists of a shock front followed by a plasma sheath in which the field intensity is high and turbulent. The amplitude of decrease is related to the field magnitude and the speed of the cloud. Both shocked plasma and the magnetic cloud are influential in determining the time profile of these decreases. In our view it is not the magnetic field strength or the topology alone which is responsible for the cosmic-ray depression. The most likely additional effect is the increased degree of turbulence.

1. Introduction

In view of the current problem (see Duggal *et al.*, 1983; Newkirk *et al.*, 1981) of understanding the solar cycle modulation of galactic cosmic rays and the possibility of a direct or indirect link between the long-term and transient variations of cosmic rays, it is important that the mechanisms which produce the latter are completely understood. In particular, the study of Forbush decreases has assumed greater importance recently with the resurgence of the idea that the cumulative effect of Forbush decreases can explain the 11-yr, long-term variation in cosmic-ray intensity (Lockwood and Webber, 1984).

Intense interplanetary magnetic fields are of basic importance to solar wind physics, magnetospheric physics and cosmic ray physics and play an important role in the modulation of galactic cosmic rays (Burlaga and King, 1979). Barouch and Burlaga (1975) found that the individual magnetic enhancements are generally associated with depressions in cosmic ray intensity and Barouch and Sari (1976) have further demonstrated that these depressions are not related to turbulence or random motions in the field and only the large-scale features of interplanetary magnetic fields are important. How-

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ever, Nishida (1982) has emphasized the importance of scattering by turbulent magnetic field in producing the transient modulation.

Recently, by selecting the key days characterized by IMF intensity $\geq 9\gamma$ the cosmic-ray data from 1965–1976 were analysed by the method of superposed epochs (Duggal *et al.*, 1983). They have demonstrated that days characterized by high IMF magnitude are associated with intensity decreases and maximum cosmic-ray intensity variations associated with high IMF intensity occur one day after the key days characterized by the field departures from the average value. This result was interpreted to indicate that the modulation mechanism becomes efficient only when the plasma engulfment of the Earth extends at least a gyroradius beyond 1 AU. Furthermore, the polar nucleonic intensity shows a prolonged recovery time (7–10 days) following magnetic enhancements. These results suggest that, on average, the IMF intensity variations which are presumably related to disturbances travelling from Sun are effective transient modulators.

However, these analyses are exclusively confined to the relation of cosmic ray intensity to the IMF strength, irrespective of the origin of its change which can be produced by a wide variety of physical mechanisms ranging from flare-produced interplanetary shocks to stream–stream interaction. It remains to be determined whether the physics of cosmic ray modulation within these interplanetary structures is the same (see also Duggal *et al.*, 1983). In a recent study of the time behaviour of galactic cosmic-ray intensity, Burlaga *et al.* (1984) concluded that the long-term modulation is associated with two types of large-scale systems of flows, one containing a number of transients such as shocks and post-shock flows, the other consisting primarily of a series of quasi-stationary flows following interaction regions containing a stream interface and often bounded by a forward–reverse shock pair. They further suggested that understanding of the physical mechanisms involved in the modulation process will require detailed analysis of individual flow systems and their effects on cosmic rays. Using a power spectral technique Goldstein *et al.* (1984) have found that the spectral signatures of the two types of regimes (transient and co-rotating) are different. The transient flows at 1 AU tend to have smaller correlation lengths and larger magnetic helicity scale lengths than do the co-rotating flows. These results indicate that the structure of the magnetic field in transient systems is more complex and less coherent than that of co-rotating streams. This may occur because the large-scale turbulent interactions are stronger in transient flows. The total fluctuating magnetic energy in a transient system is typically higher than that in co-rotating system.

From a statistical analysis Burlaga and King (1979) found that 92% of the intense magnetic fields ($> 13\gamma$) observed at 1 AU during solar cycle 20 (1963–1976) were associated with shocks, stream interfaces or cold magnetic enhancements. During 1973–1975, interface-associated enhancements occurred 3.5 times as frequently as shock-associated enhancements and during an earlier period (1967–1969) when the Sun was more active, shock-associated enhancements occurred 1.2 times as frequently as interface-associated enhancements. The frequency of cold magnetic enhancements was the same in both periods. Enhancements of all types were more frequent by a factor of

1.4 for 1973–1975 period than the 1967–1969. The average maximum field values associated with both shocks and stream interfaces showed no significant difference in the two periods considered. The cosmic-ray intensity at 1 AU was higher in 1973–1975 than in 1967–1969, though there were more magnetic enhancements in the former period. Yet Barouch and Burlaga (1975) found that individual magnetic enhancements are generally associated with depressions in cosmic-ray intensity. Thus it seems that the nature of magnetic enhancements is more important than the total number of enhancements in modulating cosmic rays (see also Burlaga and King, 1979).

The existence of unusual magnetised clouds of plasma emitted by the active Sun was proposed by Morrison (1954) as a cause of worldwide decreases in cosmic ray intensity lasting for days and correlated roughly with geomagnetic storms. Klein and Burlaga (1982) have defined a magnetic cloud as a structure of radial dimension ~ 0.25 AU (at 1 AU) in which the magnetic field strength is higher than average and the field direction changes nearly monotonically from large southern (northern) to large northern (southern) directions. The field geometry in such a magnetic cloud is consistent with a magnetic loop (Burlaga *et al.*, 1981). Burlaga and Klein (1980) have discussed two magnetic clouds one of which was associated with an unusual cosmic-ray depression while no appreciable depression in cosmic-ray intensity was found in association with the other.

Forty-six magnetic clouds were identified in the interplanetary data obtained near Earth between 1967 and 1978 and classified into three classes corresponding to the association of a cloud with a shock, a stream interface or a cold magnetic enhancement (Klein and Burlaga, 1982). In the superposed epoch plots, the maximum field strength is found to be approximately the same for each class of the cloud and the temperatures are low in all the three classes of clouds. The observed physical characteristics of the magnetic clouds and their rate of occurrence suggests that many or all clouds might be related to coronal mass ejections (Klein and Burlaga, 1982). Subsequently Burlaga *et al.* (1982) have shown that a magnetic cloud (observed by Helios 1 on 20 June, 1980) was the interplanetary manifestation of the coronal mass ejection (CME) observed on June 18, 1980. Later, Wilson and Hildner (1984) further confirmed this association at least for shock-associated clouds observed by Klein and Burlaga (1982).

Newkirk *et al.* (1981) have suggested that the interplanetary manifestations of coronal mass transients (ejections) may play an important role in galactic cosmic ray modulation and Burlaga (1983) pointed out that detailed studies of relations between magnetic clouds and cosmic rays have not been made but they are obviously worth taking. From a recent statistical study by Hundhausen *et al.* (1984) it is apparent that coronal mass ejections that are accompained by flare-eruptive prominence-X-ray-type II–IV-radio events remain at relatively low latitude throughout the activity cycle. These energetic events vary in frequency in the ecliptic plane by a factor of 3.5 through the cycle, in contrast to the almost constant overall CME count. Thus it will be interesting to investigate these most spectacular CMEs as the source of rare Forbush decreases of cosmic rays (Wagner, 1984).

In view of the known characteristics of magnetic clouds it seems important to investigate, in detail, the cosmic-ray intensity variations in relation to these clouds of different categories.

In this analysis, firstly we have performed the superposed epoch analysis, using Deep River super neutron monitor data and the data of cloud observation at the Earth as the epoch day, for three classes of clouds separately. Secondly, some individual events are studied for more specific investigation. The various interplanetary parameters associated with some of these clouds are then used to study the time profile and other characteristics of large-amplitude transient decreases (Forbush-type) in cosmic-ray intensity, which are generally observed in association with shock-associated clouds.

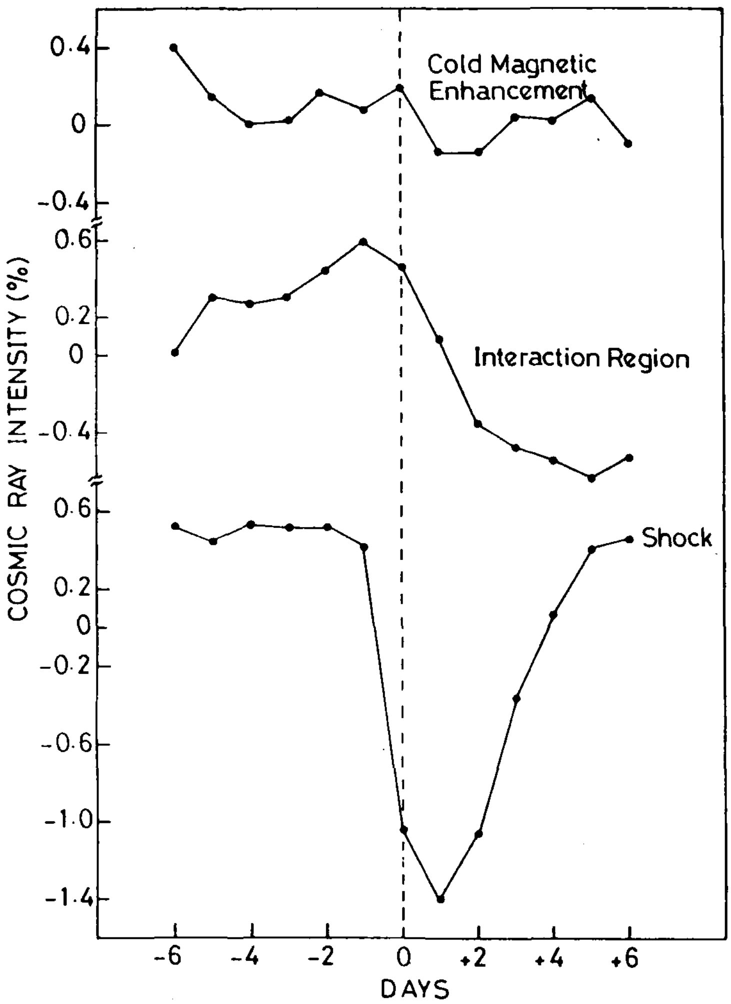

Fig. 1. Cosmic-ray intensity reduction by three classes of clouds. 0 is the arrival day of the cloud.

2. Results

2.1. Magnetic Clouds and Cosmic-Ray Intensity Variations

In Figure 1 we have shown the superposed epoch plots of cosmic ray intensity data from the Deep River neutron monitor corresponding to three classes of clouds. It is found that the decrease in cosmic ray intensity, with the clouds preceded by a shock, is higher in comparison to the decreases observed in association with the other two classes of clouds and the decrease starts earlier than the arrival of the clouds. Moreover, the recovery is complete in nearly a week. The decrease in cosmic ray intensity in relation to the cloud followed by a stream interface is much smaller than the one mentioned above. The decrease time is also elevated and the onset of the decrease takes place on the arrival of the cloud. The decrease observed in association with the third category of clouds, i.e., clouds associated with cold magnetic enhancement is of still smaller amplitude and duration. However, in this case also, the decrease in cosmic-ray intensity starts when the cloud arrives at the Earth.

2.1.1. *Magnetic Clouds Following Shocks and Cosmic-Ray Intensity Variation*

In Figure 1, the profile of cosmic ray decrease related to clouds preceded by a shock resembles the Forbush-type decrease, characterised by an abrupt reduction in the flux (typically over several hours) followed by a slow recovery (often lasting several days or even weeks). Although it is generally agreed that these Forbush decreases are caused by magnetic field variations associated with interplanetary disturbances, there have been many suggestions for the configuration responsible. These include intense magnetic fields in a bottle configuration (Gold, 1959), magnetic bubble (Piddington, 1958) high-magnetic field created by a shock wave (Parker, 1963), a large-scale tangential discontinuity (Quenby, 1971; Lockwood *et al.*, 1975), irregularities in the magnetic field (Morrison, 1956; Laster *et al.*, 1962), a series of directional discontinuities (Barnden, 1973), a magnetic blob (Barouch and Burlaga, 1975; Kane, 1977) and a spiral cone-like region which extends along the interplanetary magnetic field lines from the Sun to the radially advancing front generated by a type-IV solar flare (Iucci *et al.*, 1979a).

In recent years, in two independent studies (Burlaga *et al.*, 1981; Sanderson *et al.*, 1983), magnetic field and plasma data from spacecraft were used to analyze the flow behind an interplanetary shock. The shock was followed by a turbulent sheath in which there were large fluctuations in both the strength and direction of the magnetic field. This in turn was followed by a region (magnetic cloud) in which magnetic field vectors were observed to change by rotating nearly parallel to the plane, consistent with the passage of a magnetic loop.

The results of our superposed epoch analysis, for clouds associated with shocks, show that the cosmic ray decrease starts a day earlier than the arrival of the cloud at the Earth, minimum intensity is observed on the day after arrival and recovery is complete in approximately a week's time. Almost similar results were obtained by Duggal *et al.* (1983) from superposed epoch analysis of polar nucleonic intensity data with respect to key days characterized by magnitude of IMF $\geq 9\gamma$ irrespective of their origin.

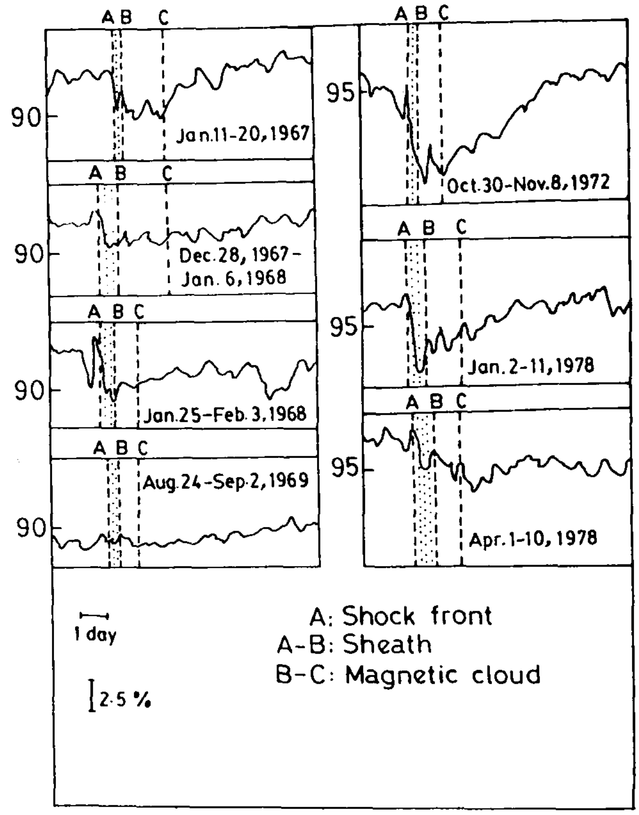

Fig. 2. Cosmic ray intensity profile observed at Deep River neutron monitor, taken from data book of National Research Council of Canada, in association with some of the clouds preceded by a shock.

To be more specific, we have plotted the cosmic ray intensity data in relation to some individual shock-associated clouds (Figure 2). Whenever the shock arrival time is not available we have used the sudden commencement of geomagnetic storms (SSC) data, since SSC can be regarded as the geomagnetic signature of the arrival of the interplanetary shock wave (Burlaga and Ogilvie, 1969). We can see from Figure 2 that, in general, the Forbush-type decrease starts at the time of arrival of the shock wave at the Earth. However, there are a few cases when no appreciable decrease in cosmic ray intensity is observed with the shock-associated clouds. Suggestions have been made in the past that the Forbush-type decrease is caused by the entry of the Earth into a loop or tongue of IMF field lines that are freshly ejected from the Sun. Cosmic-ray density in such loops was considered to be depressed because these field lines do not reach boundary regions of the heliosphere and also because the particles are cooled as the loop expands. We found (Figures 1 and 2) that in relation to shock-associated clouds, the decrease in cosmic ray intensity at the Earth starts not at the arrival of the cloud but at the arrival of the shock that precedes the cloud by a few hours. It is difficult to follow the exact time history of the events in detail, because the cosmic ray profiles vary significantly with the longitude and latitude of the observing stations. However, it is likely that the magnetic regime that contained the lowest density of galactic cosmic rays was a portion of the magnetic cloud. These results are in agreement with the view expressed by Palmer *et al.* (1978), who deduced the arrival of the loops from the bidirectional anisotropy of solar protons and electrons, that the occurrence of bidirectional anisotropy roughly coincides with the minimum of the Forbush decrease but lags behind SSC by up to 30 hours. In order to understand whether the step-like changes in the long-term modulation of cosmic rays, demonstrated for the first time by Stoker and Carmichael (1971), can be correlated to the travelling interplanetary shocks accumulating in the outer regions of the modulation cavity, Ankiewicz *et al.* (1983) have utilized the data related to shocks published by Borrini *et al.* (1982) and the pressure corrected data of the Deep River neutron monitor. They found that the superposition of the neutron monitor counting rates shows the Forbush decrease setting at shock time. Nishida (1982), by using two individual cases of magnetic loops, has also found that the decrease starts at the arrival of the shocks. Nishida interpreted these results as the indication of the enhanced efficiency of the particle scattering behind the shocks and suggested that the observation that the cosmic ray depressions are correlated with magnetic field enhancements (e.g., Barouch and Burlaga, 1975) has to be interpreted to suggest that there is an intimate correlation between the enhancement of the magnetic field strength and the intensification of the magnetic turbulence that scatters particles.

In magnetic clouds at 1 AU the pressure, principally due to the high magnetic field strength, is generally higher than the ambient pressure, suggesting that the clouds might be expanding as they move away from the Sun. Klein and Burlaga (1982) argued that between the Sun and 1 AU, magnetic clouds expand at the rate of approximately one half of the local Alfvén speed. If this expansion continues beyond 1 AU, one should find that the radial dimension of the magnetic clouds beyond 1 AU should be larger than 0.25 AU, assuming that the clouds are stable enough to maintain their identity beyond 1 AU. Subsequently, Burlaga and Behannon (1982) observed magnetic clouds between 2–4 AU in the solar wind data collected by Voyagers 1 and 2 indicating that they are stable enough to persist without major changes out to such distances. The average radial extent of the clouds observed at these distances was 0.47 AU, compared to 0.25 AU for clouds observed at 1 AU. From this they estimated that the clouds were expanding at a speed of the order of 45 km s^{-1}. The clouds observed at these distances ($\sim$ 2–4 AU) were also found to be characterized, as before, by higher than ambient (pre- and post-cloud) field strengths and generally lower than ambient plasma temperature. These observations, together with the radial extent of the clouds, suggest that the clouds were continuing to expand, even at distances of 2 AU and greater, at a speed of $\sim$45 km s^{-1}.

Parker (1963) has theoretically estimated the relative contributions of the sweeping back of cosmic rays by the shock wave front and deceleration in the expanding volume behind the front, in transient intensity reduction. He has shown that the cooling of cosmic ray particles due to expansion behind the shock can reduce the density of particles at a given energy as effectively as the sweeping does and, hence, the particles behind the shock would be cooled faster than in the unperturbed state while they are in the region of faster expansion. We shall discuss the duration of engulfment of the Earth by magnetic clouds (which may be related to its size) related to the decrease time and recovery time of Forbush-type decreases in a later section.

2.1.2. *Magnetic Clouds Preceding Interaction Region and Cosmic-Ray Intensity Variation*

Klein and Burlaga (1982) found that nearly 30% of the magnetic clouds observed at 1 AU during 1967–1978 were associated with co-rotating stream interfaces. The plasma parameters following the clouds associated with a stream interface are typical of those in co-rotating streams. These clouds were all ahead of the interface, never behind, suggesting that they are transient events, possibly swept up by streams, rather than features of co-rotating steams in the interplanetary space. The superposed epoch analysis results of cosmic ray neutron monitor data, using the arrival of these interface-associated magnetic clouds as the epoch days, show that a depression of smaller amplitude than those with shock associated clouds and of larger duration follows the arrival of the cloud at the Earth (see Figure 1). It is also seen from this figure that even six days after the cloud reaching the Earth, there is no appreciable recovery in the intensity of cosmic rays.

Periods of enhanced solar wind speed have been associated with coronal holes and active regions, which themselves are characterized by entirely different features. Coronal holes are regions of low density and temperature and occur in weak, open, diverging unipolar regions (see, e.g., Zirker, 1977), whereas the active regions show a complex magnetic structure including closed field zones and evolve rapidly when, for example, energetic flares occur in such regions. Remarkable differences are, therefore, expected to be found also between the interplanetary parameters characterising streams from the two regions. Also the galactic cosmic ray modulation should be different for the two kinds of stream. By identifying two classes of fast solar wind streams, one presumably coming from coronal holes and the other coming from active regions producing type-IV solar flares, Iucci *et al.* (1979b) showed that during the high-speed streams presumably coming from coronal holes the cosmic-ray intensity is depressed, the time behaviour of the depression follows the time profile of the wind speed and the streams coming from active regions are accompained by Forbush decreases whose amplitude and time behaviour are not directly related to the speed increase (see also, Venkatesan *et al.*, 1982). Morfill *et al.* (1979), using the interplanetary data for 13 co-rotating high-speed streams have also found that a cosmic-ray intensity decrease occurs which is coincident with the passage of the leading edge of the co-rotating high-speed solar wind streams and the minimum cosmic-ray intensity is reached approximately at the end of the stream associated magnetic field enhancement.

Murayama *et al.* (1979) did a multiple regression analysis of the cosmic ray intensity to the solar wind velocity and IMF strength, and found that the enhancement of the latter is more effective than that of the former in reducing the intensity. They also noted that magnetic field enhancements associated with solar flares produce a greater depression in cosmic-ray intensity as compared with those associated with co-rotating interaction regions and they related this to the observation that the field enhancements of the former kind tend to accompany greater fluctuations in the field direction than those of the latter kind.

We see that, in spite of the fact that the maximum field strength is approximately the same for the clouds associated with shocks and interfaces (Table I), the decrease in cosmic-ray intensity is smaller when due to interface associated clouds than when due to shock-associated clouds. Moreover, the time profile of modulated intensity is also different. In the case of shock-associated cloud the decrease profile is Forbush-type, i.e., an abrupt intensity reduction followed by a quasi-exponential recovery lasting several days (Forbush, 1938). However, in the case of the cloud followed by stream interface there is a depression in cosmic-ray intensity lasting several days though much smaller in magnitude than shock-associated clouds.

TABLE I

Average properties of different types of clouds

Cloud type	No.	Average field (γ)	Average speed (km s^{-1})	Average travel time (hr)	Mean duration (hr)	Associated cosmic-ray decrease (%)
Shock-associated	14	$\simeq 12$	460.0	90.6	26.6	$\simeq 1.8$
Interface-associated	16	$\simeq 12$	411.1[a]	105.0[a]	20.8[a]	$\simeq 1.0$
Cold magnetic enhancement-associated	16	$\simeq 12$	382.4[a]	109.9[a]	30.0[a]	$\simeq 0.35$

[a] From Wilson and Hildner (1984)

2.1.3. *Magnetic Clouds Associated with Cold Magnetic Enhancement and Cosmic-Ray Intensity Variations*

The third category of clouds are associated with cold magnetic enhancements, which are possibly the result of a special source on the Sun or a dynamical interaction near the Sun although the actual cause is unknown (Burlaga and King, 1979). Very low temperature regions (VLT) were identified by analysing the interplanetary plasma and magnetic field data (Geranios, 1982). It was suggested that the VLT are observed not because the corona was locally cold but because in the solar wind steeper temperature gradients were present because of closed structures. Most of the VLT in IMF showed characteristic variations favourable for closed structures in the solar wind (Geranios, 1982).

From Figure 1 and Table I, we see that the decrease in cosmic-ray intensity in relation to clouds associated with cold magnetic enhancements is smaller in comparison to the decrease in relation to clouds associated with shocks and interaction regions. Moreover, the decrease starts when the clouds associated with cold magnetic enhancements are observed near the Earth. The transient modulation is, in this case, not of longer duration. The observed magnetically closed structures in the solar wind containing low-temperature interplanetary plasma were recently examined in relation to cosmic-ray flux decreases (Geranios and Rosenbauer, 1983). It was suggested by these authors that small-amplitude cosmic ray decreases seem to be related to the observed magnetically closed regions in the solar wind.

2.2. Physical properties of shock-associated magnetic clouds and associated cosmic-ray variations

We have seen that the transient modulation of cosmic-ray intensity is related, in general, to the clouds of all the three categories. However, the time profile and amplitude of cosmic-ray modulation for the three types of clouds is different. The Forbush-type transient modulation is related, generally, with the cloud preceded by a shock. We have thus used the cloud and shock parameters to further study the various features of the associated modulation.

2.1.1. *Magnetic Cloud and Cosmic-Ray Decrease Durations*

As shown in Figure 3, the time taken for the decrease, from the onset time, to reach the minimum value of intensity, does not depend on the duration of the cloud. But the

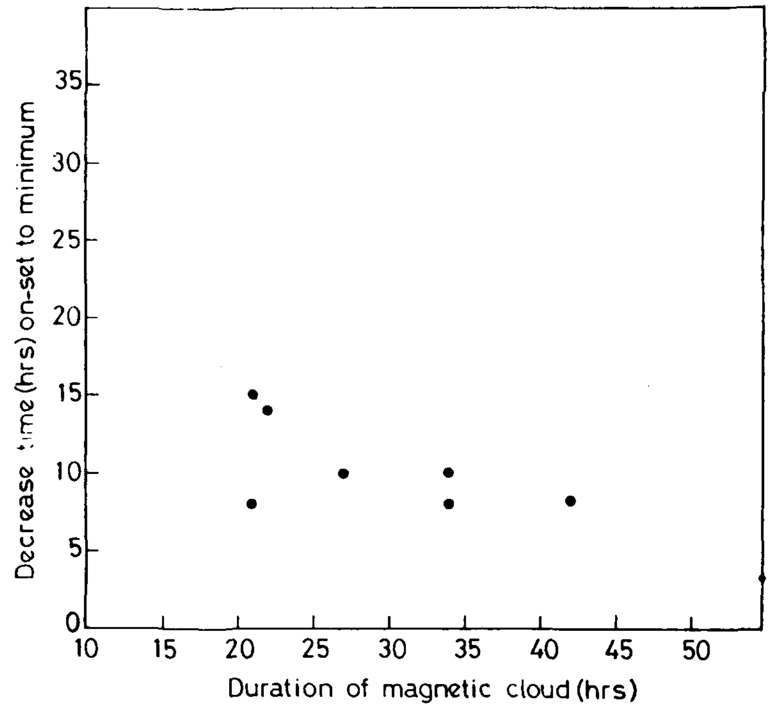

Fig. 3. Relationship between the duration of the cloud and decrease time (onset to minimum intensity).

recovery time of these decreases does seem to be dependent on the duration of observation of the clouds (Figure 4), i.e., the recovery time is, in general, larger for larger duration clouds. Though our results show the above mentioned behaviour, there is still need for more data in order to verify this result conclusively. The observed duration of the cloud will depend upon the size and/or speed of the cloud. Since the clouds are observed to be expanding to distances of at least 4 AU (Burlaga and Behannon, 1982), they are more likely to be important at larger distances as far as the recovery time is concerned. From the study (Van Allen, 1979) of cosmic-ray intensity at 1 AU, 6.97 and 15.91 AU and his findings that a magnetized plasma cloud moved outward and that the recovery times at these distances were, respectively, ~6, 22, and 150 days, it may be possible that some of the magnetic clouds move to such large distances and might also be expanding while moving to such distances. It has also been mentioned by Lockwood and Webber (1977) that the modulating regions associated with Forbush decreases were propagating several astronomical units beyond the Earth.

2.2.2. *Amplitude of Decrease and its Relation to Field Magnitude and Speed of Shock-Associated Clouds*

Figure 5 shows the dependence of the amplitude of decrease to the peak IMF intensity presumably associated with shock-associated clouds. The maximum field intensity used may be that of the compressed region between the cloud and the shock front or that

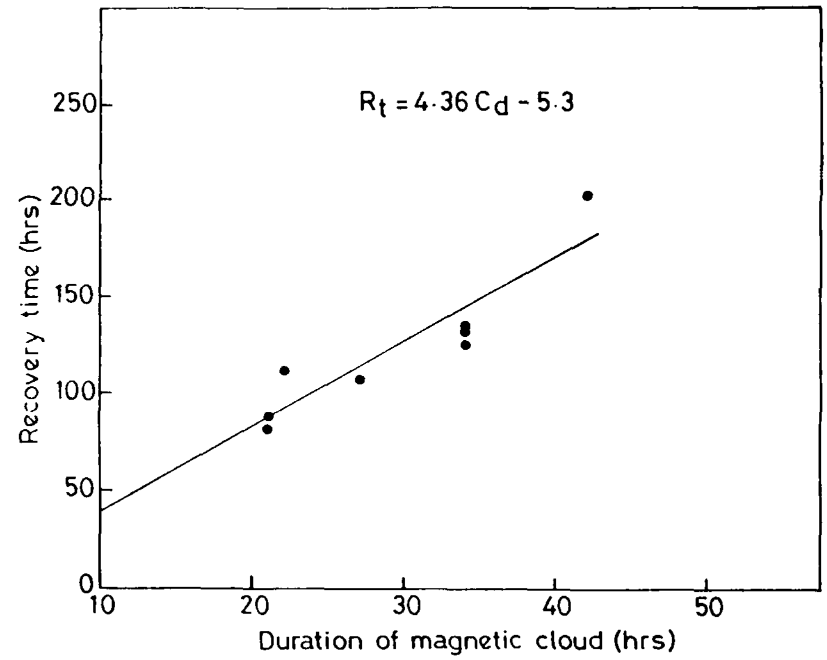

Fig. 4. Relationship between the duration of the clouds and the recovery time of Forbush decreases (minimum to complete recovery). The best fit straight line for this relationship is obtained by the method of least squares.

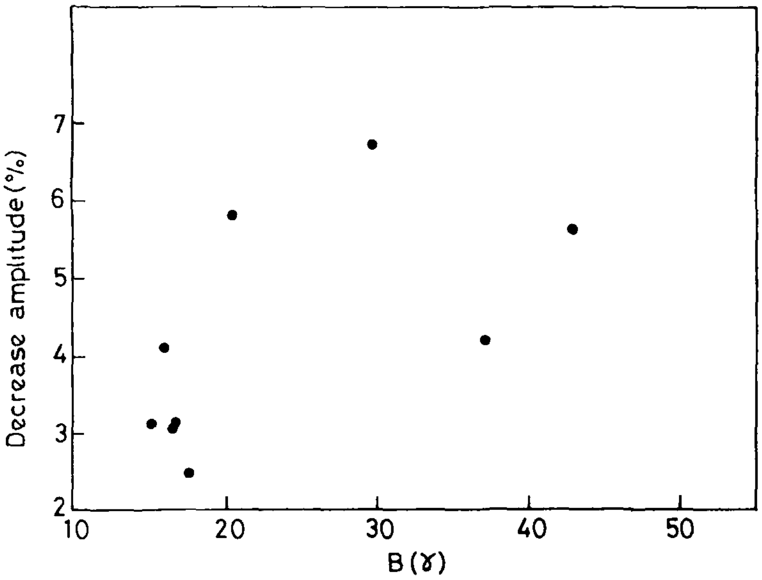

Fig 5 Relation between the amplitude of decrease in cosmic-ray intensity and the maximum field intensity

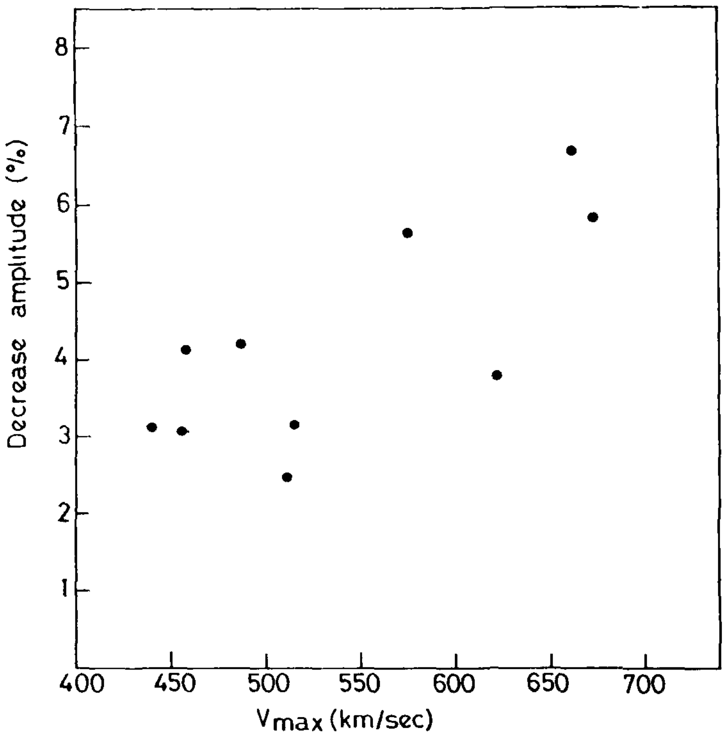

Fig 6 Relation between the amplitude of decrease and the maximum speed of the cloud

of the cloud itself. Since the onset of decrease generally coincides with the shock arrival time and the duration of the Forbush decrease is observed to be much longer than the duration of shock plus cloud, we do not distinguish here between the field intensity associated with the compressed sheath and the magnetic cloud. From Figure 5, we see that, in general, the amplitude of decrease is higher for higher field intensity. Barouch and Burlaga (1975) have found that cosmic ray depressions are correlated with the magnetic field enhancements. Duggal *et al.* (1983), using superposed epoch analysis, found that the amplitude of decrease is higher for higher IMF magnitudes when $B > 6\gamma$. It is possible that there may be a correlation between the enhancements of field strength and the intensification of magnetic turbulence as suggested by Nishida (1982).

We have also attempted to study (Figure 6) the amplitude of the decrease in relation to the increase in maximum solar wind velocity observed in association with these shock-associated clouds. In general, the increase in amplitude is larger when the cloud velocity is higher.

3. Discussion

In spite of the facts that, for all the three categories of clouds, the maximum field strength is the same, the basic structure of the field is also similar, and their temperatures are all low; also that the three types of clouds might be simply different manifestations of a single phenomena (e.g. coronal mass ejection), we still find that there is a large difference in the time profile of the transient decreases associated with these three types of clouds.

The decrease in cosmic ray intensity associated with clouds preceded by shocks starts not at the arrival time of the clouds but earlier. From a more detailed study, we find that the onset of these decreases, as observed on the Earth, is almost coincident with the shock arrival at the Earth. However, it can be easily seen that the number of Forbush decreases are higher than magnetic clouds preceded by shock, identified by Klein and Burlaga (1982) during the period 1967–1978. In their survey of ISEE-3 data, Sanderson *et al.* (1983) claim to have identified several events of the type reported by Burlaga *et al.* (1981) and Klein and Burlaga (1982). Certainly there will be more mass ejections and more shocks than these observed clouds. The shocks are followed by a turbulent sheath of ambient plasma in which there may be large fluctuations in both the strength and direction of the magnetic field. This, in turn, is followed by the mass ejecta which is driving the shock. The shock and associated ejecta both seem to be important in determining the time profile of the decrease. The field magnitude and the speed of this modulating region (which we consider from the front of the shock to the rear of the cloud) both seem to be related to the magnitude of the decrease. The duration of the cloud observation at the Earth (which may be related to its speed and/or size) is likely to be related to recovery time of the decrease.

The clouds associated with the interface after reaching the Earth may produce depressions in cosmic-ray intensity for a longer period. The amplitude of depression in this case is smaller than those produced by shock-associated clouds.

The clouds associated with cold magnetic enhancements, on the other hand, may be capable of producing a depression of smaller duration and amplitude.

The reason for these different time profiles related to these categories may be looked for in the following differences associated with these clouds: the field strength and the pressure is higher ahead of the clouds associated with shocks, due to shock compression, and the speed of these clouds are higher than those of cold magnetic enhancement and interface-associated clouds. Moreover, the sizes of shock-associated clouds are also found to be greater than the cold magnetic enhancement-associated clouds. For clouds associated with interfaces the field strength is not enhanced ahead of the cloud, but is enhanced behind the cloud owing to the interaction region that follows the cloud. The clouds associated with interfaces are followed by fast streams of plasma whereas the clouds associated with cold magnetic enhancements are neither associated with field enhancements nor high-speed streams preceding or following the cloud but the field enhancement is confined only to clouds and they are at rest relative to the ambient solar wind.

Barouch and Burlaga (1975) have studied the association of occurrence of transient decreases in cosmic-ray intensity with the presence of magnetic 'blobs' in the interplanetary medium and found a good correlation between them. However, a number of attempts to correlate the magnitude and extent of magnetic blob with the magnitude of decreases have generally not been successful because other parameters associated with these 'blobs' would differ considerably from one event to another.

As we have discussed earlier, the results of our analysis for shock associated clouds show a sharp onset at the time of shock arrival and then slower recovery lasting a few days. Such Forbush decreases in cosmic-ray intensity can be produced by reflection due to kink of the magnetic field lines at the shock front (Parker, 1963), increased modulation associated with the disturbed region behind the shock (Nishida, 1982), a barrier mechanism involving large-scale tangential discontinuity (Quenby, 1971), particle drift in an enhanced magnetic field by the post-shock region (Barouch and Burlaga, 1975) or the energy loss due to a cooling mechanism inside the shock (Thomas and Gall, 1984). These processes are not mutually exclusive and more than one may be effective (McDonald *et al.*, 1981). It is difficult to identify the relative contribution of various mechanisms although the presence of a sharp onset at the time of shock arrival indicates that a barrier mechanism such as Parker's (1963) shock front or Quenby's (1971) tangential discontinuity plays an important role in initiating a Forbush decrease. Since the magnetic clouds are expanding behind the sheath, as they move away from the Sun, it is also possible that the cosmic rays might also be decelerated in an expanding cloud or in a sheath as proposed by Laster *et al.* (1962). The possibility of some additional mechanism, apart from the particle reflection at the shock front, was also suggested by the observation of Forbush decreases at several AU from the Earth (McDonald *et al.*, 1981).

The tangential discontinuity may not be the main cause, as it occurs at the boundary between the shocked medium and the driver gas. The shock front itself is not sufficient to act as a barrier. The additional effect, in our opinion, is the increased degree of turbulence behind the shock front This leads to a smaller diffusion coefficient and acts as a barrier

The cosmic-ray profile observed in association with clouds followed by interaction regions may be explained as follows. the reduced diffusion inside the cloud may be responsible for the start of a depression However, these clouds are driven by high-speed streams, presumably coming from coronal holes. These streams will be effective in keeping the cosmic-ray intensity depressed, probably by increased convection, as long as they persist. Moreover, it has been reported that the field enhancements associated with interaction regions tend to accompany lesser fluctuations in the field directions than those associated with transient events such as solar flares (Goldstein *et al.*, 1984) Thus the hinderence in diffusing the cosmic-ray particles may not be so effective in this case. However, the cosmic-ray intensity reduction by diffusion in interaction regions is not ruled out as fluctuations in the field direction (though lesser) are present in these regions. Discussing the effect of co-rotating interaction regions on galactic cosmic rays, Morfill *et al.* (1979) have reported that the diffusion coefficient is reduced in the region between the streamline interface and the reverse shock.

Cold magnetic enhancement-associated clouds may produce small amplitude depressions of short duration. The mechanism which is involved, in this case, so that the magnetic structure influences the flow of galactic cosmic rays, as suggested by Geranios and Rasenbauer (1983), could be a different diffusion coefficient of cosmic rays inside this structure from that outside and perhaps the enhanced magnetic field could screen out some of the cosmic rays.

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INTENSITY VARIATION OF COSMIC RAYS NEAR THE HELIOSPHERIC CURRENT SHEET

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Abstract Cosmic ray intensity variations near the heliospheric current sheet both above and below it have been studied during 1964–76 Superposed epoch analysis of the cosmic ray neutron monitor data with respect to sector boundaries (i e heliospheric current sheet crossings) has been performed In this analysis we have used the data from neutron monitors well distributed in latitude over the Earth's surface First this study has been made during the two solar activity minimum periods 1964 65 and 1975 76 using the data from Thule (cut-off rigidity 0 GV) Deep River (cut off rigidity 1 02 GV) Rome (cut-off rigidity 6 32 GV) and Huancayo (cut-off rigidity 13 45 GV) neutron monitors We have also analyzed the data from Deep River Rome and Huancayo neutron monitors for whom we have the data for full period (1964 76) by dividing the periods according to the changes in solar activity interplanetary magnetic field polarity and coronal holes All these studies have shown a negative gradient with respect to heliomagnetic latitude (current sheet) These results have been discussed in the light of theoretical and observational evidences Suggestions have been given to overcome the discrepancy between the observational and theoretical results Further possible explanations for these observational results have been suggested

INTRODUCTION

Since Wilcox and Ness (1965) discovered the sector structure of the interplanetary magnetic field (IMF) and their first study of the effects of sectors in the IMF upon the cosmic ray intensity a number of other studies have been made by many authors, on the relation of IMF sector boundaries with geophysical phenomena as well as cosmic ray intensity variations The decrease in cosmic ray intensity after the boundary passed across the Earth were pointed out by Duggal and Pomerantz (1977) from an analysis of neutron monitor data from two polar stations These results were used to determine the radial density gradient Recently cosmic ray intensity variations around IMF sector boundaries were studied by Fujimoto *et al* (1981) These authors found that cosmic ray density is high near the sector boundary irrespective of the IMF polarity change and interpreted this as an effect of modulation due to decrease of solar wind velocity near the boundary

Three dimensional magnetic configuration of the heliosphere is of considerable importance in understanding the spacial variation of cosmic ray intensity It appears that the Sun has a tilted dipole Also it has now generally been accepted that it is the rotation of the tilted dipole and of the current sheet with respect to the rotation axis of the Sun which causes the alternating polarity of the IMF observed in the interplanetary space (Schulz 1973 Saito 1975 Svalgaard and Wilcox, 1976 Smith *et al* 1978) rather than the so called sector structure Thus for a simple tilted dipole the Earth (or a fixed point in the interplanetary space) is located above the current sheet for about half the days of the solar rotation and below it for the rest period During the period when the solar dipole moment is directed northward we should observe an outward directed magnetic field when the Earth is located above the current sheet and inward directed magnetic field when the Earth is located below the current sheet (cf Akasofu 1982) The concept of wobbling dipole and of the current sheet has been confirmed by Thomas and Smith (1980) by using space probe data

Many changes have been observed in the characteristic of cosmic ray modulation after the reversal of the solar poloidal magnetic field in the solar cycle 20 In order to explain such anomalies in solar modulation many theoretical workers have incorporated, in their models a current sheet which is responsible for producing sector structure in the IMF and the effects of gradient and curvature drifts (Jokipii *et al* 1977 Moraal *et al* 1979 Erdos and Kota 1980) There has been however little discussion on the contribution that might be made to the fluxes by particles streaming into the solar system from directions perpendicular to the ecliptic plane Mathews *et al* (1971) and Hedgecock *et al* (1972) emphasized the possible importance of the off ecliptic control of the cosmic ray modulation and it has been suggested (Hedgecock *et al* 1972) that galactic cosmic rays and their modulation with the solar cycle may be more strongly influenced by latitudinal gradients than by radial gradients Thus the evaluation of the contribution of the mechanisms, such as particle drifts (Jokipii *et al.*, 1977) and/or latitudinal gradients (Roelof *et al.*, 1981) is needed. Jokipii and co-workers have achieved some success with a model in which changing geometry of the field and its influence on the drifts of the particles is the dominant mechanism of cosmic ray modulation. Since the role of changing three-dimensional geometry of interplanetary space is largely speculative and will remain so until *in-situ* observations of such parameters as the velocity of the solar wind, the spectrum of magnetic fluctuations, and cosmic ray fluxes can be extended well above the ecliptic and combined with the three dimensional models of cosmic ray propagation in the heliosphere, it seems prudent to try to extract some knowledge about these parameters from indirect methods.

DETERMINATION OF HELIOMAGNETIC LATITUDINAL GRADIENTS

In accordance with present models of IMF (Schulz, 1973; Saito, 1975; Svalgaard and Wilcox, 1976; Smith *et al.*, 1978) a warped current sheet is assumed to separate the two hemispheres of opposite magnetic polarities. The field is assumed to point outward (positive) everywhere above the current sheet and inward (negative) below the current sheet for the post-1969 epoch. The reversed field is assumed for the pre-1969 epoch. As the Sun rotates every 27 days the Earth will be located above the current sheet (in the North) for a certain period(s) and below (in the South) during the rest of the period. This passage of the neutral sheet or heliospheric current sheet at the location of the Earth is interpreted as the sector boundary crossing. The Earth sees a reversal of the magnetic polarity (positive to negative or negative to positive) on each crossing of the current sheet.

The sector pattern and the heliospheric current sheet changes with solar cycle and the direct evidence for the solar cycle variation in the configuration of the current sheet was noted by Bruno *et al.* (1982). They found that in 1976 the sheet was nearly parallel to the solar equator and symmetrically warped so that an observer near the Equator would see four sectors and a similar pattern was observed in 1964–65 one cycle earlier. The latitudinal extent of the current sheet was found to be on average 8° and the maximum extent 15°. In 1975, the inclination of the dipole was $\sim 10°$ and the current sheet was warped asymmetrically at times. Zhao and Hundhaussen (1981) inferred that in 1974 the Sun's magnetic field was predominantly inclined at $\sim 30°$ with respect to the Sun's rotation axis. Thus these isolated studies taken together suggest that the inclination of the dipole axis with respect to the solar rotation axis decreased with decreasing solar activity, and the two axes were nearly aligned near solar minimum (Burlaga, 1983).

The available *in-situ* measurements are limited (in latitude) by the fact that most spacecraft orbits lie in or near the ecliptic plane. This limitation, however, is less severe than it seems, for the Sun's rotation axis is tilted 7.5° with respect to the normal to the ecliptic, allowing us to sample a solar latitude range of at least 15°. Whenever the Sun's magnetic dipole is inclined with respect to the rotation axis the available range of magnetic latitudes may be even larger. For example, Zhao and Hundhaussen (1981) examined measurements of the bulk speed and density of solar wind obtained at 1 a.u. in 1974, and they found changes which could be interpreted as latitudinal variations with respect to a magnetic dipole axis inclined $30° \pm 10°$ from the rotation axis. Specifically, they found that the speed was smallest near the magnetic equatorial plane (which would correspond to the heliospheric current sheet) and increased with latitude. The Sun is uniformly quiet perhaps during a year or so around the sunspot minimum period. Around this period of solar minimum the solar magnetic field takes on the form of a tilted dipole, the corona is dominated by coronal holes which extend nearly to the Equator from the magnetic poles, and the heliosphere takes on the form of a simple tilted dipole with opposite magnetic polarity in opposite hemispheres and a somewhat corrugated current sheet at the magnetic equator (cf., Hundhaussen, 1977). Such epochs are also ones of great stability of the corona and the interplanetary medium suggests that the heliospheric plasma, magnetic fields and cosmic rays are in an approximately steady state. The rotation of the Sun and the heliosphere then provides the means for an Earth-based detector to sample heliomagnetic latitudes up to $\pm 30°$ every rotation rather than $\pm 7°$ every year (Newkirk and Lockwood, 1981).

A systematic change of the orientation of the solar dipole axis during a solar activity cycle was also proposed by Saito (1975). It has been suggested that the bending of the current sheet arises as a result of North–South asymmetry in solar activity (Mori and Saito, 1979). Also, it is now generally accepted that it is the rotation of the tilted dipole and the current sheet with respect to the rotation axis of the Sun which causes the alternating polarity of the radial component of the IMF which is observed in the interplanetary space (Smith *et al.*, 1978). Thus, for a simple tilted dipole the Earth is located above the current sheet for about 27/2 days and below it for about 27/2 days. During the period when the solar dipole moment is directed northward, the radial component of the IMF is directed outward (away) when the Earth is located above the current sheet and inward (toward) when the Earth is located below the current sheet (Hakamada and Akasofu, 1981). This concept of wobbling solar dipole and of the current sheet has been confirmed by Thomas and Smith (1980). So from the above discussion it can be inferred that the Earth's distance with respect to solar magnetic equatorial plane and thus to the current sheet varies systematically as the Sun rotates every 27 days.

In the present paper we present neutron monitor data from Thule (cut-off rigidity 0 GV), Deep River (cut-off rigidity 1.02 GV), Rome (cut-off rigidity 6.32 GV) and Huancayo (cut-off rigidity 13.45 GV), well distributed in latitudes. Chree epoch method has been applied, using the sector boundary crossing data (Svalgaard, 1976; Wilcox and Scherrer, private communication) as the epoch day, to study the latitudinal gradient of cosmic rays in the heliosphere. Since the Sun is almost quiet around sunspot minimum period, we first applied the above method to study the variation of cosmic ray intensity near the heliospheric current sheet (both above and below) during the two solar activity minimum periods 1964–65 and 1975–76. The interplanetary field lines were directed inward above the current sheet and outward below it during 1964–65, while the field lines were outward above the current sheet and inward below it during the period 1975–76. Then the periods of study (1964–76) have been divided into two groups 1964–68 and 1969–76, when the IMF in the Northern and Southern Hemispheres have reverse configuration. This study has also been made, separately, for the periods when the northern magnetic pole of the Sun was negative (1964–68) and positive (1972–76) and also during the period when the polarity reversal took place (1969–71). In this way a systematic study has been made to study the density gradient of cosmic rays, in the heliosphere, with particular emphasis of the effect near the heliospheric current sheet by using a relatively simpler method, during different epochs of solar cycle, as discussed above. Due to non-availability of the direct data by spacecrafts from higher latitudes (since most spacecraft orbits lie in or near the ecliptic plane) this simple approach of determining the latitudinal gradient of cosmic rays in the heliosphere seems quite informative. The latitudinal distribution of cosmic ray in the heliosphere has been of considerable interest and discussion in the last few years, both from theoretical and observational points of view (as discussed in a later section). The implications of our results are discussed.

LATITUDE GRADIENT OF COSMIC RAY INTENSITY IN THE HELIOSPHERE—THEORETICAL ASPECT AND EXPERIMENTAL RESULTS

There are two indirect methods to detect the perpendicular cosmic ray density gradients using cosmic ray detectors on the Earth. One is to use the Earth's excursion of $\pm 7.25^\circ$ in heliolatitude during the year, which can give rise to an annual wave in cosmic ray intensity. In this method annual and semi-annual components are evaluated by means of Fourier analysis (Antonucci *et al.*, 1978). These authors have found that the cosmic ray gradient, perpendicular to the solar equatorial plane, regularly changes its direction at the solar activity maximum, displaying a 22-year periodicity.

The second method of detecting perpendicular cosmic ray density gradient at the Earth makes use of contribution of the drift term $\mathbf{B} \times \nabla N_p$ to the solar diurnal cosmic ray variation ($\mathbf{B}$ is the IMF vector, ∇N_p is the cosmic ray density gradient perpendicular to the ecliptic plane). This method has been described by Swinson (1970) and Hashim and Bercovitch (1972). Their results are consistent with a southward perpendicular gradient during 1967 and 1968. This method was further used by Kananen *et al.* (1981) and Swinson and Kananen (1982) for the analysis of longer period. They found the results which point to a cosmic ray density gradient, perpendicular to the ecliptic plane, pointing southward from 1965 to 1969 and changing to northward pointing gradient after the reversal of Sun's polar magnetic field in 1969–71, extended up to 1975. In a later extension of the above work Swinson (1983) using the underground cosmic ray telescope data from 1975 to 1982, found no sustained perpendicular gradient (either northward or southward) throughout this period of time, though solar polar field reversal took place in 1980–81 (Howard and Labonte, 1981). In a similar analysis on geomagnetically quiet days, Badruddin *et al.* (1984) have concluded that the North–South asymmetry in solar activity seems to be influential in determining the latitude gradient of cosmic ray flux.

To explain the observed solar semi-diurnal cosmic ray variation, Subramaniam and Sarabhai (1967) and Lietti and Quenby (1968) postulated the existence of a cosmic ray density gradient perpendicular to the ecliptic plane. The proposed gradient required a minimum density of cosmic rays in the ecliptic plane, with the density increasing with distance both above and below the plane. Later Subramaniam (1971) found results indicating a cosmic ray density increasing with distance below the ecliptic plane and decreasing above it during the period 1962–1965. Kane (1968) demonstrated the variability of the perpendicular gradient during different periods between 1960 and 1967. His data indicate that for 1965–1966 any perpendicular gradient existing was small, which is consistent with little or no perpendicular gradient during that period. Kane's data, however, do indicate a southward perpendicular gradient for 1967 and 1968.

Although it has long been recognized that there is considerable azimuthal and latitudinal variation in the heliosphere, modulation models have until recently ignored this structure and considered mainly spherically symmetric cases. However, as shown by Fisk (1976), three dimensional effects (off-ecliptic variations) can substantially affect near ecliptic measurements like radial gradients or spacial anisotropies. Recently attempts have been made to incorporate these three-dimensional effects into the modulation theory of cosmic rays. The impetus for this is the direct observation by *Pioneer* space probes of the interplanetary magnetic field structure (cf., Smith and Wolfe, 1979). The importance of the above large scale structure of the field lines lies in the transport of cosmic rays across the field lines due to curvature drifts. Even in the absence of any latitude dependence of parallel and perpendicular diffusion coefficients, the radial diffusion coefficients will vary with latitude as the Archemedian spiral angle will vary with latitude. But the parallel and perpendicular diffusion coefficients will vary due to scattering by waves in the solar wind plasma varying with the heliographic latitude. Hence it is quite clear that any theory of transport of cosmic rays in the interplanetary space has to incorporate three dimensional effects (Ramadurai, 1981).

The variation in the modulation of cosmic rays with latitude in the model of Fisk (1976) is caused solely by the expected latitude variations in the direction and amplitude of the IMF. Levy (1978) in his attempt to explain the observed semi-annual variation in the galactic cosmic ray flux observed at Earth, pointed out that the general dipole-like symmetry of the IMF produces a heliospheric latitude variation in the density of the modulated cosmic rays.

Current interest in the ability of the solar wind to modulate the cosmic ray intensity is focussed on the evaluation of the importance of particle drift motion caused by gradients in and curvature of IMF in exchanging cosmic ray particles between solar equatorial and solar polar latitudes (Jokipii *et al.*, 1977; Jokipii and Levy, 1977; Jokipii and Kopriva, 1979; Isenberg and Jokipii, 1978, 1979; Jokipii and Davila, 1981; Kota, 1979; Moraal *et al.*, 1979; Kota and Jokipii, 1982, 1983). Jokipii and Kopriva (1979), on the basis of a two-dimensional model, in which drift plays a dominant role, predicted a sharp increase in cosmic ray density away from the solar magnetic equator in 1969–81 and a sharp decrease during 1958–68 and 1981–92. In other words they have provided numerical solutions of modulation equations including drift motion which yield a positive gradient towards higher heliolatitudes if the northern solar field is predominantly outward while the gradient is negative if the general solar field is reversed. These papers have emphasized the importance of drifts and revealed the existence of a new type of modulation based on the balance between drift and energy loss in which diffusion plays a negligible role. Jokipii and Thomas (1981) have suggested that the changes in the waviness of the interplanetary current sheet can be an important effect in producing solar modulation of galactic cosmic rays and any process which increased the waviness of the current sheet would have a similar effect. On the basis of a three-dimensional model for solar modulation including drifts, Moraal *et al.* (1979) have shown that the particles seen at the Earth cross the boundary of the modulation cavity at very different heliolatitudes, depending on the sign of IMF. However, the off-ecliptic gradient is always positive towards the poles. Moraal *et al.* (1979) also claim that in the post-1970 period, the equatorial intensity should be higher due to reduced latitudinal gradient, a prediction supported by stratospheric monitoring by Charkhchyan and Stozhkov (1981). Potgieter and Moraal (1983) presented further numerical solutions of the two-dimensional steady state transport equation in the three-dimensional axisymmetric heliosphere and found that the intensity at the poles is greater than at the Equator for both pre-1970 and post-1970 but the latitudinal gradients are larger for the pre-1970 period. Erdos and Kota (1981) have made calculations using a model based upon calculating energy losses along regular particle trajectories in an IMF model incorporating a wavy neutral sheet. They calculate the density distribution of the 50 GV cosmic rays for the two periods before and after the Sun's polar field reversal and find that the latitudinal gradient changes sign with polarity reversal on the Sun; cosmic ray intensity increases towards poles for the 1969–80 magnetic configuration, while it decreases away from the solar equator for opposite magnetic configuration. These results closely resemble those obtained by Jokipii and Kopriva (1979) at lower energies.

However, Newkirk and Lockwood (1981), employing a latitude defined by K-coronometer data (magnetic latitude) and using the cosmic ray data of a neutron monitor, find that the cosmic ray gradient does not change sign but that the intensity is always higher at the Equator. In other words they found a negative correlation between cosmic ray intensity and the Earth's heliomagnetic latitude (i.e. the distance from the current sheet) for both halves of the 22-year cycle. They used the Mt. Washington neutron monitor data, for the two selected minimum periods, September–October 1965 and May–June 1975. This result is seemingly in contradiction to the expectations of the drift model which for a flat neutral sheet, at least, predicts a fairly sharp increase of cosmic ray intensity away from the current sheet for 1975 (Jokipii and Kopriva, 1979). Further, the results of Newkirk and Lockwood (1981) point to a higher gradient for 1975 than for the 1964 period. Kota and Jokipii (1982, 1983) in a subsequent simulation extended the full two-dimensional calculations, and including diffusion, to a three-dimensional computational code which permits a wavy current sheet to be incorporated. These calculations present the first study of the steady state modulation of cosmic rays by solar wind in which all major transport effects– convection with solar wind, anisotropic diffusion, particle drifts and energy loss—are included in a fully three-dimensional model. In general the results support their earlier, less comprehensive calculations which included drifts and in addition, they show that including diffusion as well as drifts produces qualitatively new behaviour near the wavy current sheet. In particular they found that the intensity decreases away from the current sheet for both signs of solar magnetic field, in contrast with the earlier results which do not include diffusion. This is at least in qualitative agreement with the results obtained by Newkirk and Lockwood (1981). But there is an apparent discrepancy in magnitudes since the calculations of Kota and Jokipii (1982, 1983) give a steeper regression for the pre-1969 period than they do for the post-1969 period. Newkirk and Lockwood (1981), on the other hand, observed a steeper regression for 1975 than 1965 period.

Studying the 22-year variation of the solar diurnal variation, based on the diffusion–convection equation which has a self-consistent expression concerning the electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, Nagashima and Munakata (1983) have noted that in the post-1969/70 period, the near-Earth density of the cosmic rays is higher than that in the pre-1969/70 period and the latitudinal density gradient is considerably higher.

Use of the conventional guiding center theory for drifts has demonstrated that the magnitude of the latitudinal gradient in cosmic ray intensity can be profoundly altered depending on the phase of the cycle of the solar magnetic field. Using numerical simulation techniques, drift motion and perpendicular diffusion is studied by Moussas *et al.* (1982), and it was suggested that the perpendicular diffusion may be an important process for the propagation in the IMF. The perpendicular diffusion effects on the gradient of cosmic rays do not depend on the sign of the solar field and hence the enhanced importance suggested makes any off-ecliptic gradient less sensitive to the 22-year cycle.

It is only recently that it has been possible to directly detect cosmic ray gradients that vary in heliolatitudes. This has been achieved by simultaneous use of multiple spacecrafts (McKibben *et al.*, 1979; Roelof *et al.*, 1981): these measurements are for a limited period of time and at relatively low energies.

RESULTS AND DISCUSSION

Figure 1 shows the result of a superposed epoch analysis (with reference to IMF sector boundaries or heliospheric current sheet crossings) of nucleonic intensity data from four neutron monitors, well distributed in latitude from the pole to the Equator. The two periods selected for the analysis are the minimum activity periods before and after the reversal of the solar magnetic field around the solar maximum period in solar cycle 20. It is assumed that the current sheet separates positive (negative) fields in the Northern Hemisphere from negative (positive) fields in the Southern Hemisphere and generally the fields above, or North, of the current sheet are inward or negative and fields below, or South, of the current sheet are outward or positive in the period 1964–65. But the fields are directed in reverse directions above and below the current sheet in the period 1975–76. Thus in 1964–65, in a positive sector the observer is thought to be below the current sheet and in a negative sector it is above the current sheet and passes through the current sheet on the day of the sector boundary crossing. The situation is reversed in the period 1975–76. It may be mentioned here that we have considered, for our analysis, the days when there is one particular polarity at least for 5 days before the sector boundary crossing and the reverse polarity, also at least for 5 days after the sector crossing.

We can see from Fig. 1 that the cosmic ray intensity decreases for a few days (both after $-+$ and $+-$ sector crossing) and then it starts recovering towards maximum intensity which is observed on the day of sector boundary crossing. In other words it can be said that the cosmic ray density is higher near the current sheet and it decreases as the heliomagnetic latitude increases. This is true for both the periods considered, i.e. for 1964–65 and 1975–76. It can also be seen from the figure that the latitudinal gradient is nearly symmetrical both above and below the heliomagnetic equator during these periods of minimum activity.

Another result that can be inferred from these figures is that the negative latitudinal gradient is much steeper during the period 1975–76 than 1964–65. Newkirk and Lockwood (1981), using the data from a mid-latitude station for 2 months duration during each period, have also found similar results. Potgieter *et al.* (1980) found a significant difference between the 1965 solar minimum response function of sea level neutron monitors and those for the period of solar minimum during 1976. The

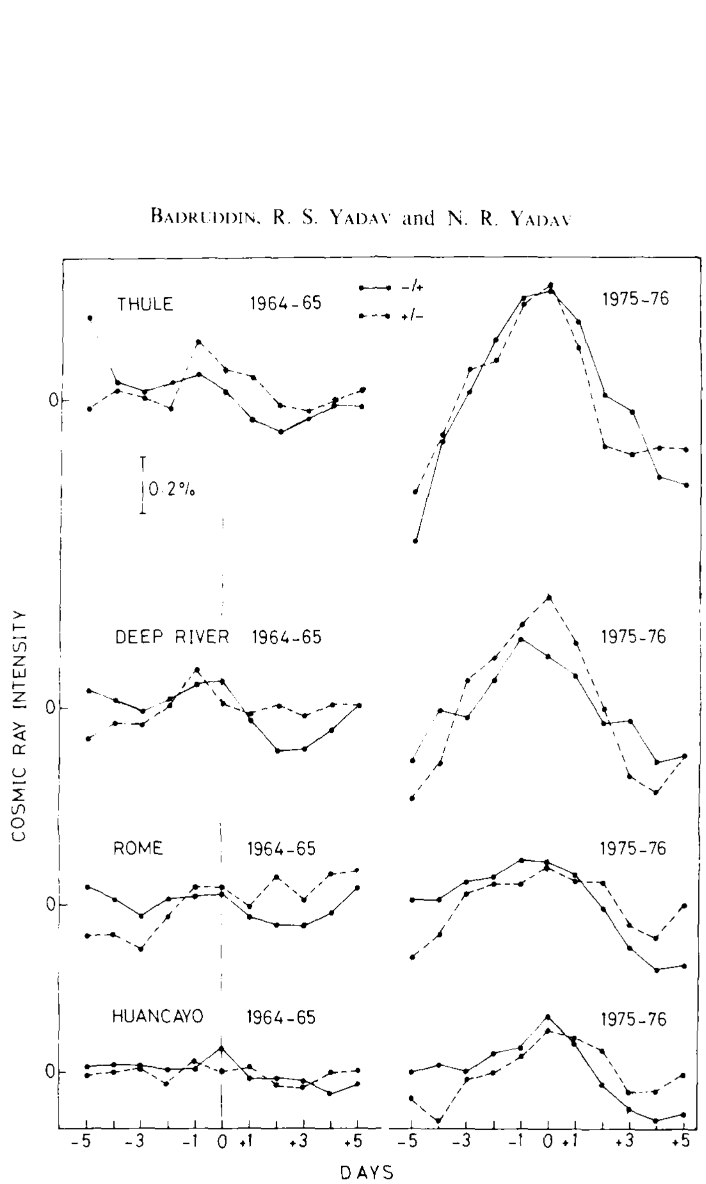

FIG. 1. RESULTS OF THE SUPERPOSED EPOCH ANALYSIS FOR ± 5 DAYS (ZERO DAY CORRESPONDS TO THE IMF SECTOR BOUNDARY CROSSINGS) FOR THE GALACTIC COSMIC RAY INTENSITY AT THULE, DEEP RIVER, ROME AND HUANCAYO FOR THE PERIODS 1964–65 AND 1975–76.

difference suggests that the cosmic ray spectrum was harder during 1965 than in 1976. This difference in cosmic ray spectra at subsequent solar minimum is, as suggested by Potgieter *et al.* (1980), related to the polarity of the interplanetary magnetic field.

Although the drift flux in the formulation which consists of contribution from curvature and gradient drift was included in the original formulations of modulation theory (Axford, 1965; Parker, 1965), the observed sector structure of the IMF was thought to minimize its importance. With the recognition of the importance of off-ecliptic effects and the disappearance of sector structure (Smith *et al.*, 1978) the necessity of taking the drift term into account was felt. In a series of recent papers (Jokipii *et al.*, 1977; Jokipii and Kopriva, 1979; Jokipii and Davilla, 1981; Kota, 1979), the importance of particle drifts in cosmic ray transport in interplanetary space has been re-emphasized. They stress that the drifts dominate the motions of substantial portion of galactic cosmic ray particles. However, doubts exist as to whether the drift formulation is correct for the condition of large scale magnetic turbulence found in the solar wind (Lee and Fisk, 1981). Evidence has been cited both supporting (Antonucci *et al.*, 1978; Levy, 1978; Shea and Smart, 1981; McKibben *et al.*, 1979) and denying (Evenson *et al.*, 1979; Cooper and Simpson, 1979) the dominance of drifts. Thomas and Gall (1982) studied the propagation of cosmic rays reaching the Earth by simulation of particle trajectories in the models of heliospheric magnetic fields, including the effects of CIRs. They concluded that strong field gradient associated with CIRs greatly perturb the drift pattern anticipated for simple Parkerian fields and thus the expected streaming of cosmic rays from over the poles or along the current sheet during the consecutive cycle no longer holds. However, Moussas *et al.* (1982) have shown that gradient and curvature drifts can be present even in a highly perturbed field and thus they can have some influence in cosmic ray modulation.

Newkirk and Lockwood (1981), by employing a latitude defined by K-coronometer data (heliomagnetic latitude), found that the cosmic ray gradient does not change but the intensity is always higher at the Equator. This result is contrary to the 2-dimensional calculation of Jokipii and co-workers which included drift but neglected diffusion. Recently, Kota and Jokipii (1982, 1983) presented the results using a full 3-dimensional model which incorporates all known important effects on particle transport, i.e. particle drifts, convection with solar wind, energy loss and anisotropic diffusion. They find substantial effects due to the warp of the current sheet. Among other things they showed that the intensity may decrease away from the current sheet for both signs of magnetic field, in contrast with inferences from earlier more approximate calculations. These earlier calculations could not explain the observations of Newkirk and Lockwood (1981) in which intensity decreased away from the current sheet for both signs of IMF. However, from the 3-dimensional computational code which permits a wavy current sheet to be incorporated, the results are shown to be in general agreement to the observations of Newkirk and Lockwood (1981), but these calculations of Kota and Jokipii (1982, 1983) predict a much steeper latitudinal gradient during the period before the reversal of the magnetic field in the solar cycle 20. However, our analysis shows that the latitudinal gradient is much steeper during 1975–76, which is the period after the reversal of the polarity of the magnetic field, as compared to the period 1964–65, when there is much smaller gradient in latitude. Moussas *et al.* (1982) have studied the energetic particle propagation in IMF by the computer simulation of its motion in order to calculate perpendicular diffusion coefficient and average drift velocity in an ensemble of particles. They neglected the electric field contribution ($\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, $\mathbf{V}$ is the solar wind velocity). Their results show that the gradient and curvature drift can be present even in highly perturbed fields and thus can have some influence in cosmic ray modulation. They also found that small scale random fluctuations in the field gradient and curvature can be at least of some importance in causing the perpendicular diffusion. While studying, theoretically, the 22-year variation of the solar diurnal anisotropy, based on the diffusion–convection equation which has a self-consistent expression concerning the electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, Nagashima and Munakata (1983) have noted that in the post-1969/70 period, near-Earth density of cosmic rays is higher than that in the pre-1969/70 period and the latitudinal density gradient is considerably larger.

From the above discussion we do not intend to discuss the authenticity of the drift model; however, we do speculate that, if drifts are important in solar modulation, the discrepancy in latitudinal gradient of cosmic rays predicted by 3-dimensional drift models which include diffusion, and our observational results can be removed by including the latitude-dependent solar wind velocity, at least during periods of solar minimum. Potgieter and Moraal (1983), by including the latitude-dependent solar wind velocity in the drift model of cosmic ray transport, have found that such a dependence has an effect on modulation. Sime and Rickett (1978) have found that the source regions of the high speed solar wind are not symmetric about the rotation axis but were centered more than 30° from the rotation axis during 1973–75. From these results it can be inferred that a high speed solar wind tends to originate from the regions outside the bright belt of the white light corona. This coronal bright belt may be a manifestation of the magnetic equator (Pneuman, 1976). Thus it is reasonable to infer that the latitudinal dependence of the solar wind velocity is actually the magnetic latitude dependence (cf., Hakamada and Akasofu, 1981). These authors attempted to reproduce the 27-day variation of the solar wind observed near Earth between 1966 and 1979 by assuming a tilted magnetic dipole and a solar wind speed increasing with distance from the equator. Zhao and Hundhaussen (1981) also found that the speed was smallest near the magnetic equatorial plane (which would correspond to the heliospheric current sheet) and increased with latitude. However, the latitudinal gradient in velocity inferred by Hakamada and Akasofu (1981) was twice as large as derived by Zhao and Hundhaussen (1981).

In Fig. 2 we have shown the results of Chree epoch analysis with sector boundary passage date as the key day. In this figure the total period of solar cycle 20 is divided into two parts according to the field polarity above and below the current sheet; the period 1964–68, when the field is assumed to point inward above the current sheet and outward below it, and the period 1969–76, when the reverse field is assumed, i.e. the field pointing outward above the current sheet and inward below it. This assumption is similar to that of Erdos and Kota (1980). The negative latitude gradient is evident in both the periods. During the period 1964–68, the Earth is above the sheet (in the North) on the negative polarity days. After sector boundary crossing the Earth finds itself below the current sheet (in the South).

Solar activity was high during the period 1966–68. Moreover, the North–South asymmetry in the solar activity is also large (Badruddin *et al.*, 1983), i.e. the

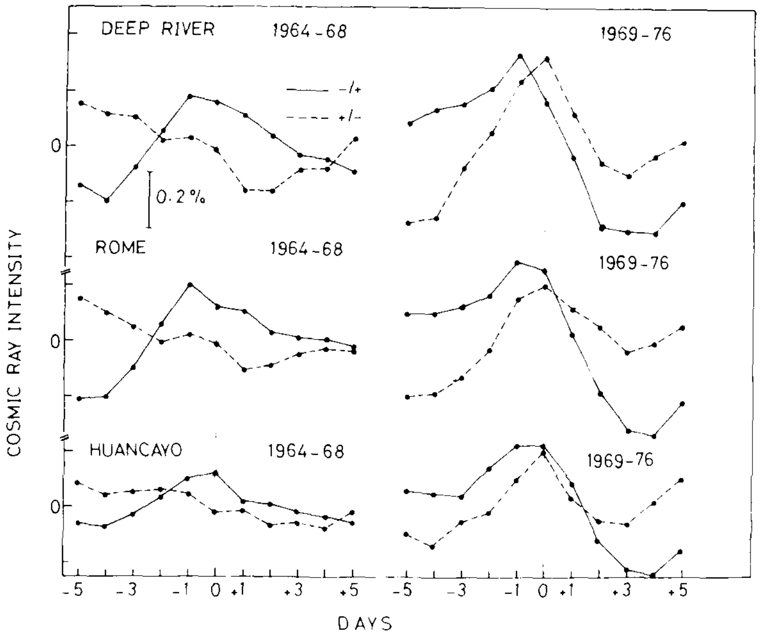

FIG. 2. SUPERPOSED EPOCH ANALYSIS RESULTS OF COSMIC RAY INTENSITY AT DEEP RIVER, ROME AND HUANCAYO WITH EPOCH OF IMF SECTOR BOUNDARY CROSSINGS FOR THE PERIODS 1964–68 AND 1969–76.

solar activity in the Northern Hemisphere was much larger as compared to the Southern Hemisphere. From the figure it can be seen that cosmic ray density is higher when the earth is located in the positive polarity region (below the current sheet) than when it is in the negative polarity region (above the current sheet). Further the density gradient is higher in the North of the current sheet.

The Chree analysis result for 1969–76 shown in Fig. 2 reveals the decrease in cosmic ray intensity when an observer moves towards higher heliomagnetic latitude. This decrease in cosmic ray intensity is much higher when the observer is moving in the positive sector (i.e. above the current sheet) than when it is moving below the current sheet. During this period the solar activity, as evidenced from solar flares, was very high in 1969 and 1970 and moreover the activity was much higher in the Northern Hemisphere than in the Southern Hemisphere. However, this activity was relatively lower during the period 1971–76 and also there was no appreciable asymmetry (on average) in the solar activity, although there was a slightly higher negative asymmetry in 1974.

In Fig. 3 we have divided the whole period of solar cycle 20 into three different periods: 1964–68, 1969–71 and 1972–76. In 1964–68, the solar activity was increasing and the coronal holes were shrinking in size. The period 1969–71 is the period of reversal of the polar magnetic field of the Sun. During this period the solar activity was very high and the coronal holes were almost absent. In the period 1972–76, the solar activity was relatively low and high speed streams were prominent as the polar coronal holes were growing in size.

The analysis of neutron monitor data shows the negative gradient with respect to the current sheet during 1969–71. Also the higher density is observed when the Earth is in the negative sector (below the current sheet) than when it is in the positive sector (above the current sheet). Further decrease in cosmic ray intensity seems higher when it moves above the current sheet than when it is moving away below the current sheet. During this period the solar activity was very high and also the North South asymmetry was quite large.

In the results shown for 1972–76, the difference in cosmic ray density gradient, when the Earth moves above the current sheet and when it moves away below the current sheet, is considerably reduced. In this period the overall North–South asymmetry in the solar activity was very small though there is slightly higher activity in 1974. However, the long-lived streams of high speed solar wind were prominent in these years. These fast solar winds flow from polar holes and extend equatorward, with slow winds occurring in a limited spacial band centered on the magnetic neutral line (Hundhaussen, 1979). A correlation between cosmic ray intensity and the size of polar coronal holes during

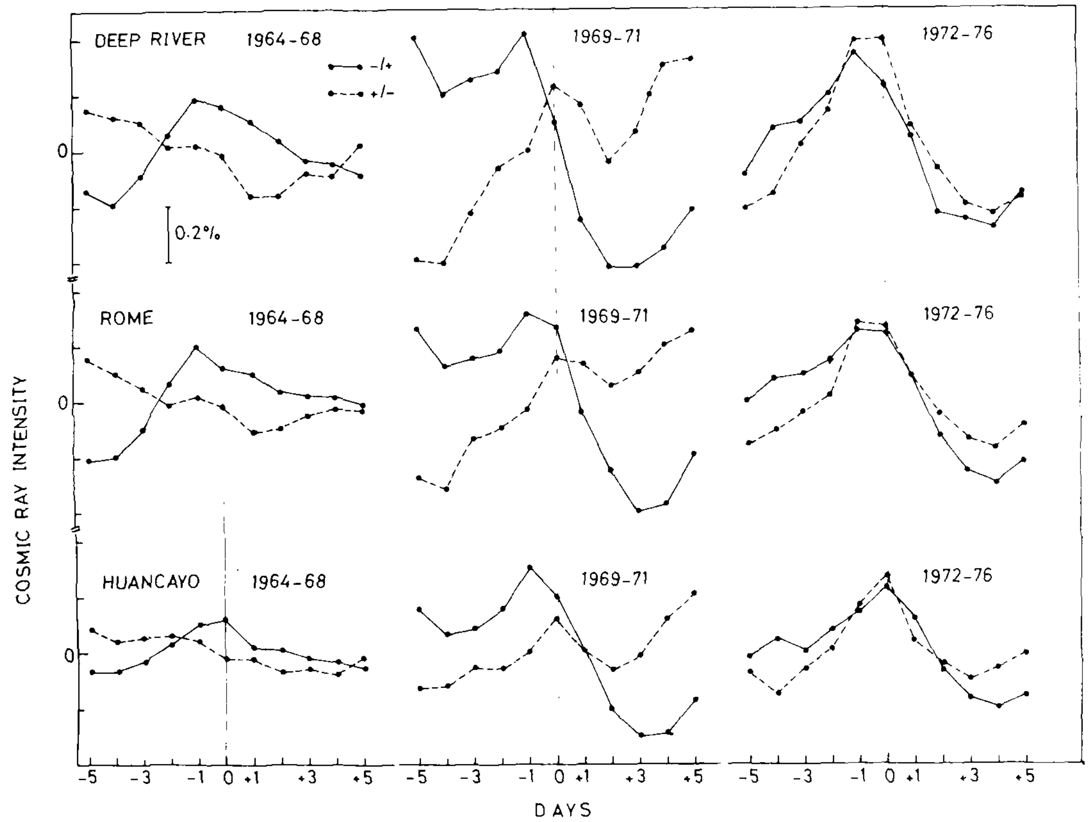

FIG. 3. SUPERPOSED EPOCH ANALYSIS RESULTS OF COSMIC RAY INTENSITY AT DEEP RIVER, ROME AND HUANCAYO WITH EPOCH OF IMF SECTOR BOUNDARY CROSSINGS FOR THE PERIODS 1964–68, 1969–71 AND 1972–76.

the period 1965–76 has been reported by Hundhaussen *et al.* (1980). They found that the coronal holes are influential in determining the 3-dimensional modulation of galactic cosmic rays in the solar system. Later, on the basis of coronal hole geometry, Ahluwalia and Riker (1981) have suggested that after 1971 electromagnetic conditions in solar corona make it easier for off-ecliptic cosmic rays to be transported from high heliolatitudes to low heliolatitude location in the solar corona. During solar cycle 20, polar coronal holes shrink in size from 1965–1967 during the ascending phase of the cycle and they almost disappeared in 1969 and 1970, which is the period of polar field reversal. However, they reappeared in 1971 and grew in size during the descending phase of the cycle, and these polar coronal holes have their larger size during the sunspot minimum (Hundhaussen *et al.*, 1980). The amplitude of the solar wind stream appears to be directly related to the size of the coronal hole (cf. Zirker, 1977). Small, low latitude coronal holes tend to be associated with relatively narrow streams (500–600 km s^{-1}) at the Earth while large coronal holes, even at mid-latitude are more apt to be associated with relatively wide streams when speed at Earth sometimes exceeds 700 km s^{-1} (Broussard *et al.*, 1978). It may be possible that the asymmetry in the size of northern and southern polar coronal holes has some influence on the differences in latitudinal gradient above and below the current sheet, especially during the descending and minimum phases of the solar activity cycle when the level of solar activity was not high and the North–South asymmetry was quite small.

We suggest that the results of our analysis can be explained as follows: as the Sun rotates the Earth's distance with respect to the current sheet varies. An observer on the Earth sees a decrease in cosmic ray intensity as it moves away from the current sheet. After a few days when it starts moving towards the current sheet, the intensity of cosmic ray particles starts increasing and the maximum cosmic ray intensity is observed near the current sheet. If the current sheet lies in the ecliptic plane, throughout the solar cycle, our results may be interpreted to indicate that the value of the density gradient pointing away from the solar equatorial plane is not symmetrical above and below it, at least during the periods of high solar activity and appreciable North-South asymmetry. Alternatively the current sheet might have been displaced from the ecliptic plane due to asymmetric activity in the Northern and Southern Hemispheres of the Sun. In such a situation the extent of the Earth's excursion in heliomagnetic latitude will be different above and below the current sheet. However, if the theoretical results showing the symmetric density gradient on either side of the equatorial plane are corrected, then the second alternative seems a more plausible explanation.

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Cosmic Ray Density Gradient & Its Dependence on the North-South Asymmetry in Solar Activity

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A systematic and detailed analysis of the diurnal anisotropy on geomagnetically quiet days has been performed using the cosmic ray intensity data for the period 1964-1979 for neutron monitors at Deep River, Leeds, Rome and Tokyo. The days have been separated according to the polarity of the IMF on that day. Appreciable difference in the amplitude and phase is found for towards and away polarity days, particularly, during the years when the solar activity is high and the north-south asymmetry is also quite large. These results on geomagnetically quiet days show some better relationship with the expected results, especially, the behaviour of the time of maximum; however, these did not show any good relationship with the expected result when all days in a year are considered. The results of the study indicate that the north-south asymmetry in solar activity is influential in determining the latitude gradient of cosmic ray flux.

1 Introduction

The existence of perpendicular density gradient of cosmic rays has been studied by separating the cosmic ray diurnal vectors into groups corresponding to the direction of interplanetary magnetic field (IMF). In the case of southward gradient and if the field is away from the sun, the resultant diurnal variation should have a larger amplitude and the time of maximum should occur earlier, whereas, if the field is towards the sun the resultant diurnal variation should have a smaller amplitude and the time of maximum should occur later. Swinson[1] and Hashim and Bercovitch[2] have applied this method for the years 1967 and 1968. Their results are consistent with the southward gradient during these years. The same method has been further applied, using the neutron and meson monitor data for the period 1965-75, for examining the nature of the perpendicular gradient before and after the reversal of the sun's magnetic pole[3,4] in 1969-71. Kananen *et al.*[3] and Swinson and Kananen[4] found that the amplitude of the diurnal anisotropy on away days exceed those of towards days during the year 1965-68 and that the reverse is generally the case after the reversal of sun's polar magnetic field in 1969-71. These data point to a cosmic ray gradient, perpendicular to the ecliptic plane, pointing southwards prior to 1969, and changing to northward pointing gradient after the reversal of sun's polar magnetic field in 1969-71 except in 1974. However, the phase does not show the effect expected from the amplitude behaviour. The difference in phase between the data for the two sets of IMF polarities is much less marked than in the case of amplitude[3,4]. No significant difference in the amplitudes and phases of the away and towards polarity days was found by Kananen *et al.*[3] and Swinson and Kananen[4] in 1969-71 at neutron monitor energies.

In order to explain the observed semi-diurnal anisotropy Subramanian and Sarabhai[5] and Lietti and Quenby[6] postulated the existence of a cosmic ray density gradient perpendicular to the ecliptic plane. The proposed gradient required a *minimum density* of cosmic rays in the ecliptic plane and rising symmetrically both above and below the plane. Later, Subramanian[7] obtained results indicating an increase of cosmic ray density with distance below the ecliptic plane and decreasing above it during the period 1962-65. Using the ground based observations, Pathak and Agrawal[8] have recently shown that the symmetrical cosmic ray gradients above and below the solar equatorial plane is not observed in the latitude range $\pm 7.25°$ from equator, during the period 1973-75.

The north-south asymmetries (in the solar activity) may have implications in the structure and evolution of the heliosphere, its current sheet and the cosmic ray propagation[9]. The possibility of the deflection or deformation of the current sheet near the sun by processes occurring on the solar surface was speculated by Thomas and Smith[10]. The bending of the current sheet arises as a result of north-south asymmetry in solar activity and the resulting predominance of one particular sector polarity arising from this asymmetry can lead to seasonal variation in cosmic ray diurnal anisotropy[11,12]. Erdos and Kota[13] have suggested that the difference in inward and outward daily vectors of cosmic ray anisotropy may originate in possible north-south asymmetry of the heliosphere.

Earlier Agrawal *et al.*[14] found that on a day-to-day basis the coherence for the cosmic ray anisotropy is better for days of low to average solar wind speed, which also is related to geomagnetically quiet days. Therefore, it would be more meaningful to use only these days for determining the annual averages of the cosmic ray daily variation, particularly, for sunspot maximum activity period, during which large number of cases of time varying isotropic changes in cosmic ray intensity are observed. In this paper, we have analyzed the neutron monitor data for the period 1964-79 for four stations, by selecting sixty most quiet days in a year and determined the amplitude and time of maximum for away and towards polarity days separately. On the basis of these results the perpendicular density gradients in relation to north-south asymmetry in solar activity are discussed. Some indirect information about the three-dimensional structure of the heliosphere especially the current sheet, that may be inferred from these results, are outlined.

2 Analysis

The hourly pressure corrected data of neutron monitors at four stations, namely, Deep River (cut-off rigidity $R_c \sim 1.02$ GV), Leeds ($R_c \sim 2.20$ GV), Rome ($R_c \sim 6.32$ GV) and Tokyo ($R_c \sim 11.61$ GV), have been analyzed harmonically for the sixty most quiet days in a year. The location and threshold rigidity of the neutron monitor stations are presented in Table 1. The amplitude and phase of daily variation are obtained for each individual day after correcting the hourly data for long term trend by subtracting the 24-hr moving average. The values of amplitude and phase of the diurnal anisotropy at the minitor, thus obtained, are transformed in interplanetary space by applying corrections for geomagnetic bending[15,16]. The diurnal cosmic ray variation vectors have been separated into groups corresponding to towards and away IMF polarities using IMF data given by Svalgaard[17] and Sheeley and Harvey[18]. The daily vectors are subsequently averaged for each year and each IMF polarity to obtain the average for different years from 1964 to 1979.

The average daily vectors are studied by appropriately grouping these years according to the level of the solar activity, its north-south asymmetry on the solar surface and magnetic field and plasma characteristics of the heliosphere. The frequency

Table 1—Location and Threshold Rigidity of the Neutron Monitor Stations

Station	Geographic location		Threshold rigidity GV	Period of analysis
	Lat. deg	Long. deg		
Deep River	46.10N	77.50W	1.02	1964-79
Leeds	53.80N	1.55W	2.20	1965-74
Rome	41.91N	12.52E	6.32	1967-75
Tokyo	35.75N	139.72E	11.61	1970-78

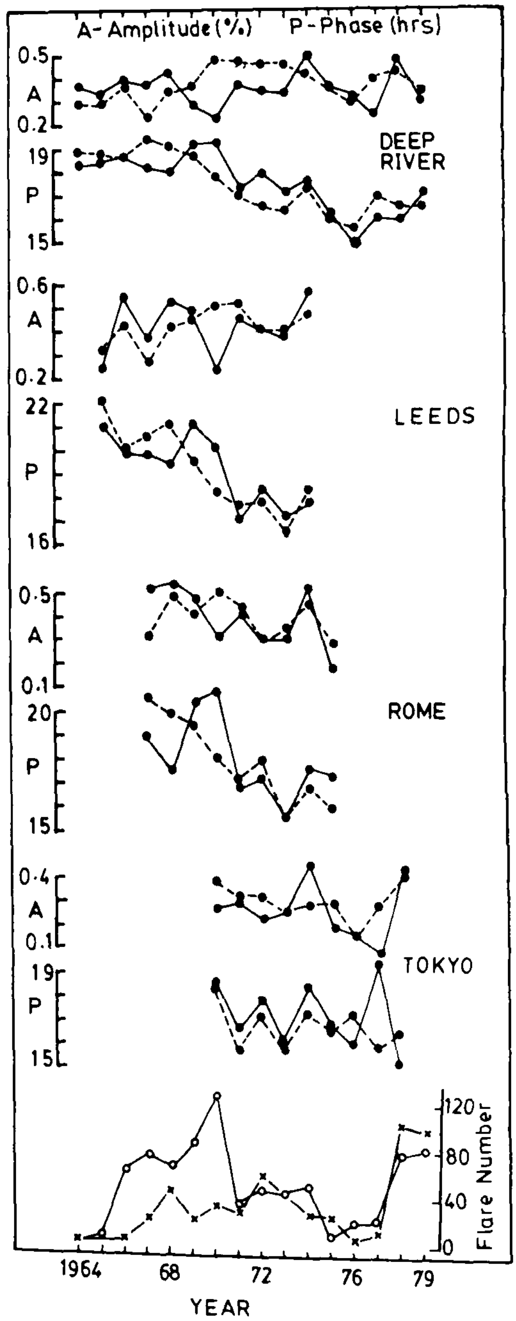

Fig. 1—Observed yearly average solar diurnal amplitudes and phases on quiet days for away polarity (solid line) and towards polarity days (broken line) calculated from Deep River, Leeds, Rome and Tokyo neutron monitor data [The number of major solar flares in northern (crosses) and southern (circles) hemispheres in respective years are also shown. The $\pm 1\sigma$ standard error for amplitudes of individual years comes between ~ 0.015 and ~ 0.045 %.]

distribution of amplitudes and phases for these days has also been discussed for each year from 1964 to 1979 by using Deep River super neutron monitor data.

3 Results and Discussion

Fig. 1 shows the yearly average amplitude and the time of maximum for each year, on geomagnetically quiet days, during away and towards polarity days. The neutron monitor data from four neutron monitoring stations, well distributed in latitude and longitude, are used. Fig. 1 shows that during 1964-68 the amplitude on away polarity days is, in general, higher than on towards polarity days, and the phase on towards polarity days is higher than the away polarity days. The differences in the amplitude and phase on away and towards polarity days are more pronounced during the higher solar activity periods (1967 and 1968). These results for 1964-68 are consistent with those suggested by Swinson[1], Hashim and Bercovitch[2], Kananen *et al.*[3] and Swinson and Kananen[4]. However, the results of Kananen *et al.*[3] for the time of maximum do not show the right type of effect as expected. The reason advanced by Kananen *et al.*[3] for unexpected results for the time of maximum of diurnal anisotropy is that this might be due to separation of days into only two groups which allows the direction of the IMF to fluctuate in wide limits within them. Using the data for three neutron monitoring stations, we found that the results for the time of maximum on geomagnetically quiet days are also, generally, in agreement with those expected from the amplitude behaviour during 1964-68, especially in 1967 and 1968. To give a better representation, we have plotted the average vectors for the period 1964-68, separately, for towards and away polarity days (Fig. 2). A microscopic representation of the diurnal amplitude and phase on day-to-day basis for these days is given in Fig. 3, which shows the frequency distribution of diurnal amplitude and phase in different years.

Since the vector representation only shows the average of all the individual values, it is the frequency plot which shows the peaks of the individual values that lie in the particular interval. The frequency diagram also shows whether the average values are of a shallow distribution or sharp peaked distribution. The difference in amplitudes and phases of away and towards polarity days is also seen from frequency distribution plot (Fig. 3) similar to those shown in Figs 1 and 2.

Kananen *et al.*[3] and Swinson and Kananen[4] did not find any significant difference in the amplitudes and phases of away and towards polarity days during 1969-71. Their results imply no density gradient (pointing northwards or southwards) during this period of reversal of sun's polar magnetic field. From 1966 to 1970, the solar activity was high and the north-south asymmetry was also quite large and positive throughout this period[19,20]. In cosmic ray modulation studies the epoch consideration in relation to the solar magnetic field polarity reversal is somewhat variable especially during 1969-71, the period of polarity reversal of solar polar magnetic field. The cosmic ray variations, depending on the polarity of the IMF show somewhat different characteristics among different periods, say between 1964-68 and 1969-79 (Refs 13, 21, 22), 1964-69 and 1970-79 (Refs 23-25), 1964-70 and 1971-79 (Ref. 26), 1964-70 and 1972-79 (Ref. 27). These results point towards the transition in cosmic ray behaviour in one or the other year during 1969-71. Thus there might be a significant difference in

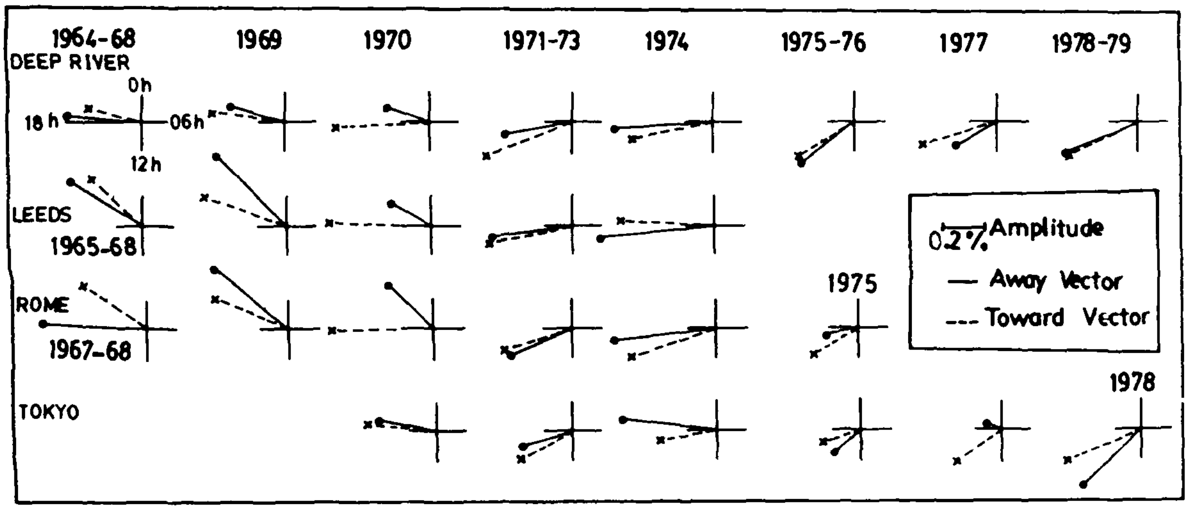

Fig. 2—Average solar diurnal vectors on quiet days for IMF away from (dots, solid line) and towards (crosses, broken line) the sun for years indicated

amplitude and phase on towards and away polarity days, at least, in 1969 and 1970. Since the north-south asymmetry during the year 1969 and 1970 is of the same sign as during 1967 and 1968 (years of high solar activity), our results may also provide some indication towards selecting the transition year for cosmic ray studies as regards the polarity of the IMF. Fig. 1 shows that the amplitude at Deep River and Leeds, which was higher for away polarity days than for towards polarity days during the years 1964-68, changed to higher value for towards polarity days than away polarity days in 1969 though at Rome similar change has been observed in 1970. However, as far as the phase is concerned, it has changed to later hours for towards polarity days than the away polarity days in 1969 at all the three stations, i.e. Deep River, Leeds and Rome. In 1970, the amplitude was much higher for towards polarity days than away polarity days and the time of

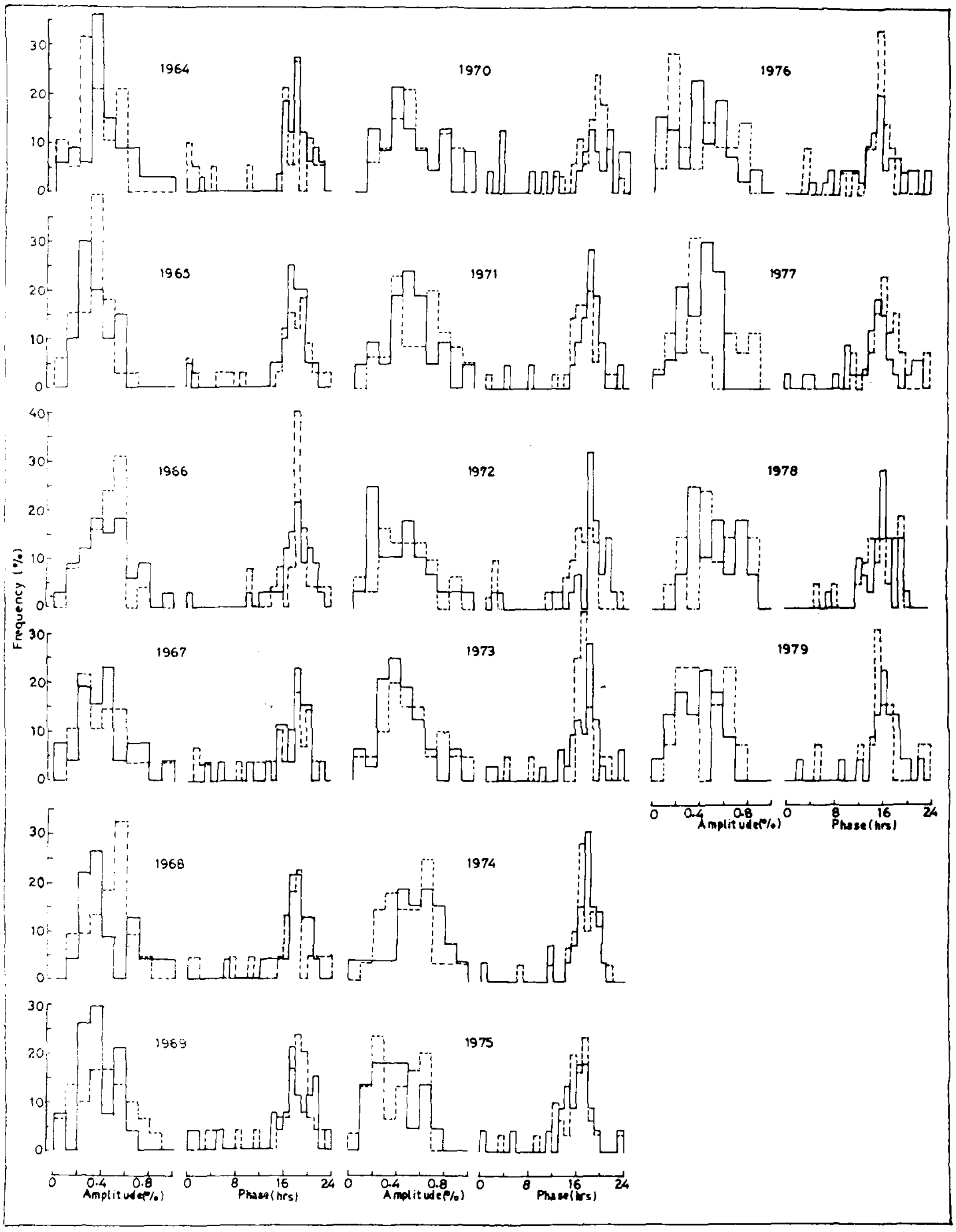

Fig. 3 Amplitude and phase distribution of the diurnal vector on quiet days for each year from 1964 to 1979 calculated from Deep River neutron monitor data, for away (solid line) and towards (broken line) polarity days

maximum was quite significantly towards later hours for away polarity days than towards polarity days. These results are also shown in the vector diagram of Fig. 2. In many earlier studies[13,21,22], it has been assumed that the IMF in northern and southern hemispheres has reverse configurations during 1964-68 and 1969-70. The north-south asymmetry in solar activity during 1969-70 was of the same sign (positive) as it was during 1967-68. Thus if the current sheet was displaced downwards due to positive north-south asymmetry during 1967-68, it will be the same case during 1969-70 too. But since the IMF polarity may be different in northern and southern hemispheres during 1967-68 and 1969-70, the reverse behaviour in diurnal amplitude and phase on away and towards polarity days during the same periods may be also due to this reason. However, in 1971, when the solar activity was quite low as compared to that in 1969 and 1970 (the north-south asymmetry was also small in this year), no significant difference in the amplitude and time of maximum for towards and away polarity days is observed at all the four stations. Only the amplitude at Deep River shows some difference for towards and away days. Similar difference at Deep River was also reported by Swinson and and Kananen[4] also.

During the period 1971-73 there was some difference in the amplitude of towards and away polarity days only at Deep River neutron monitoring station. Fig. 2 shows the average vectors for the period 1971-73 for all the four stations. During this period there was no marked north-south asymmetry as evidenced from solar flares. Hundhausen *et al.*[28] have reported the correlation between cosmic ray intensity and the size of the polar coronal holes during the period 1965-76. They attributed the solar cycle modulation of cosmic rays to the three-dimensional global characteristics of the IMF. Ahluwalia and Riker[29] have suggested that after 1971 the electromagnetic condition in solar corona made it easier for off-ecliptic cosmic rays to be transported from high heliolatitudes to low heliolatitude locations in the solar corona. A rapid rebirth of polar coronal holes, after their absence in 1969 and 1970 was observed in late 1970 (in southern hemisphere) and in early 1971 (in northern hemisphere) and a slower average growth was observed[28] during descending phase of the solar cycle. Swinson and Kananen[4] did not find a consistent northward gradient at the meson monitor energies during 1971-73, though their results point to a northward gradient in 1972 and 1973 for Deep River and Oulu neutron monitors.

An interesting behaviour is observed in 1974 when the amplitude of away polarity days is higher than the towards polarity days. Similar result was also found by Swinson and Kananen[4]. The argument advanced for this result by Swinson and Kananen[4] is that the modulation process responsible for the sharp fall in cosmic ray intensity in 1974 and then its recovery by the end of the year might have also disturbed the prevailing perpendicular gradient, particularly at lower rigidities. Ahluwalia and Riker[29] have found a transient shift in the diurnal time of maximum to later hours. To explain this they suggested that the abrupt rearrangement of the solar field in 1974 is not very conducive to the coronal transport of off-ecliptic cosmic rays; it nearly chokes off the field aligned flow of the particles, thereby permitting the diurnal time of maximum to shift to later hours. It is to be mentioned here that the north-south asymmetry in the solar activity was somewhat negative as evidenced from solar flares and, moreover, during 1973-75 the very intense solar wind streams were prominently observed.

In the solar activity minimum period of 1975 and 1976, there is no appreciable difference in the amplitude and phase values for towards and away polarity days. Fig. 1 shows these values yearwise, while the average vector is plotted in Fig. 2 and the frequency distribution for the amplitude and time of maximum in Fig. 3. The solar activity was quite low during these years and also the north-south asymmetry was very small. However, in 1977, there is some evidence for a northward pointing gradient as seen from the amplitude at Deep River and the amplitude and phase at Tokyo for towards and away polarity days. The solar activity in 1977 was not high and the north-south asymmetry was also small. However, there was an accelerated increase in the solar activity after mid-1977.

In the present solar cycle, the north polar field has reversed in mid-1980 and the south polar field in mid-1981 (Ref. 30). Prior to this polarity reversal, the solar activity in 1978 and 1979 was very high. However, the north-south asymmetry was small. We see from the results for amplitude and phase on away and towards polarity days that there is no appreciable difference in amplitude and phase for the two type of days both at Deep River and Tokyo.

From the above results we see that there is an appreciable difference in the amplitude and or phase on towards and away polarity days during the years of high solar activity and large north-south asymmetry. During the years of lower solar activity and or small north-south asymmetry this differences is not appreciable. These results indicate that the north-south asymmetry in solar activity is influential in determining the latitude gradient of cosmic ray flux. These results support the view that, at least during the period of high solar activity and appreciable north-south asymmetry, either the density gradient pointing away from the solar equatorial plane is not symmetric or the current sheet might have been displaced from the ecliptic plane. Thus it seems right to suggest[31] that in order to detect any $\mathbf{B} \times \mathbf{V} N_p$ anisotropy, the position of the neutral sheet (on average) would have to be displaced from the ecliptic plane due to asymmetric activity on the sun.

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On the Major Solar Flare Activity in Solar Cycles 19, 20 & 21 (1955-79)

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Utilizing the major solar flare data for the period 1955-79, which includes solar cycles 19, 20 and 21, a comprehensive analysis of these flares is presented. In this analysis, study is made of their distribution around the sun, both in latitude and longitude, the time latitude occurrence in solar cycles 19, 20 and 21 and their nature and frequency in northern and southern hemispheres in these solar cycles, and the change of occurrence of these flares in the course of years for both halves of the solar disk separately and also for the disk as a whole. Their relationship with sunspot numbers in different solar cycles and their occurrence frequency with increasing comprehensive flare index in general and for cycles 19 and 20 in particular (observations for cycle 21 are not complete) have also been studied.

1 Introduction

Long years of observations of various manifestations of solar activity indicate that their occurrence in northern and southern hemispheres is not uniform[1-8]. In the first quarter of this century, using the sunspot data for the period 1874-1913, the latitudinal distribution of sunspots was studied in detail[2]. The heliographic latitude distribution of optical solar flares and flares producing magnetic storms[8], polar cap absorption (PCA) producing flares[9], the coronal line intensity[6] has been studied for varying periods subsequently. The heliographic longitude distribution has also been studied, in the past, for flares which produce energetic solar particles[10,11], yellow lines[12] and optical solar flares[13].

Analyses were performed to study the north-south asymmetries in white light flares, major solar flares, complex and non-complex sunspots, and sunspot areas[7], PCA flares[9], optical flares[8], photospheric magnetic field[14], faculae[5], prominences[15] and coronal line 530.3 nm (Ref. 6). The long term variation in the energetic particle emissivity of the sun was examined[16] by the use of PCA, solar proton flux and geomagnetic data for 1941-73 period.

With limited data of large flares of importance $\geqslant 2$ for the solar cycle 19, the relationship between sunspot number and frequency occurrence of these flares has been investigated recently. Its occurrence frequency with increasing flare importance has also been discussed[17].

The relationship between the solar magnetic field and solar activity has also been extensively studied in the past. The negative polarity fields on the solar surface are closely related to the development of new solar activity[18] and the solar flare energy output bears a linear relationship with the rate of change of flux of longitudinal component of photospheric magnetic field[19].

The purpose of the present paper is to study in detail the nature and frequency of major solar flares during the different periods of solar activity cycle and in different zones of solar surface both in latitude and longitude, using the maximum available data for the solar cycles 19, 20 and 21. The peculiarity about the solar cycles 19 and 21 is that the solar activity was unusually high[17] in solar cycle 19 when compared with that for any other cycle during the last 350 years and the solar cycle 21 is the second highest cycle[20] during the last 280 years.

2 Analysis

We have carried out an extensive statistical analysis of major solar flares fulfilling the criteria established by Dodson and Hedeman[21-23] for the period 1955-79, which includes solar cycles 19, 20 and 21. Dodson and Hedeman[21-23] have devised a comprehensive flare index (CFI) which classifies a flare as major flare whenever any of the following criteria is satisfied: short wave fade (or sudden ionospheric disturbance) importance $\geqslant 3$; H_α flare importance $\geqslant 3$; 10 cm flux $\geqslant 500 \times 10^{-22}\,\mathrm{Wm^{-2}\,Hz^{-1}}$; type II bursts; type IV radio emission of duration > 10 min. Each individual item is scaled from 1 to 3 to compile the CFI. This index has the advantage of not excluding small optical events with unusually strong ionizing and radio frequency emissions.

Using these major flare data from 1955-79 we have studied their latitudinal and longitudinal distribution over the solar disk, the long term variation, their occurrence in northern and southern hemispheres of the sun and the behaviour of solar activity in the solar cycle with reference to solar latitude. We have also studied the relationship between the sunspot number and the frequency occurrence of major flares. After arbitrarily dividing the major flare events into six classes according to increasing CFI to establish a criterion for the importance of energy output, the occurrence frequency of these classes in different solar cycles is also studied.

3 Results and Discussion

3.1 Heliographic Latitude and Longitude Distribution

We have studied the heliographic distribution of major solar flares satisfying the criteria laid down by Dodson and Hedeman using the data for the periods 1955-79. The heliolatitudinal distribution of these major flares is shown in Fig. 1. The flare location has been summed up over 10 heliolatitudinal interval. The peaks in the frequency distribution, shown in Fig. 1, are located in the interval 10-20° in both the hemispheres. This clustering in the 10-20° latitude is more significant in the northern hemisphere. Out of the total events (1936) observed during 1955-79, ≈63% were observed to occur in the northern hemisphere and ≈37% in the southern hemisphere. Further, nearly 34% of the total were observed in only 10-20°N latitude interval. Almost similar results were found for optical solar flares of all importances and flares associated with magnetic storms[8]. As shown in Table 1, the north-south asymmetry is nearly same in all the latitude intervals (of 10°) up to 40° beyond which the observation of major flares is negligible.

The solar longitudinal distribution of major solar flares is shown in Fig. 2. The distribution is approximately similar in both the hemispheres, east and west. Out of the total events (1936) observed during 1955-79, ≈49% were observed to occur in eastern hemisphere and ≈51% in the western hemisphere. This heliographic longitudinal distribution of major solar flares may be represented by a Gaussian function of the type

$$f(\phi)d\phi = \alpha.\exp[\cancel{-\beta^2(\phi}-\beta^2(\phi-\bar{\phi})^2]d\phi$$

Here,

$$\alpha=6.249,\ \beta=0.007,\ \bar{\phi}=-0.576,\ d\phi=10$$

This generated function over the visible hemisphere of the sun is shown in Fig. 2 by dotted line. In this function $f(\phi)d\phi$ is the frequency of the flares in the longitude interval $d\phi$ and α, β are constants. The shallow peak in the middle of the distribution curve indicates that the frequency of major solar flares around 0° longitude is not much elevated from other higher longitude frequencies. Such curve provides a general idea about the longitudinal distribution of flares around the solar disk. The shape of curve and the

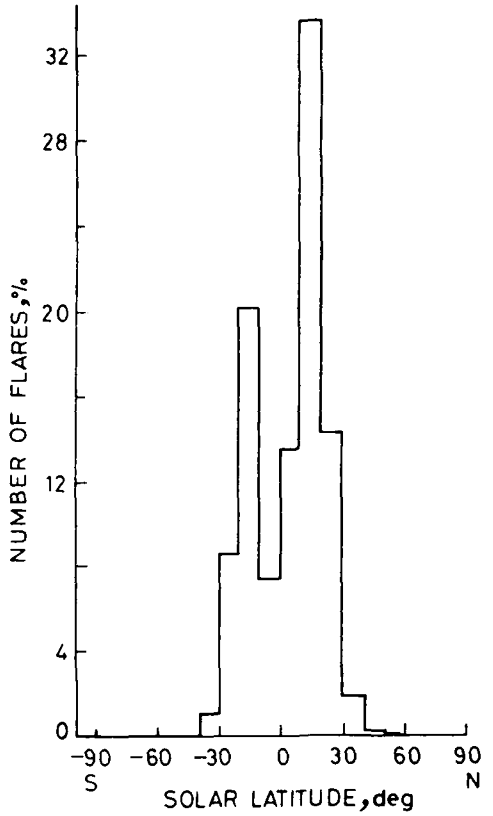

Fig. 1—Solar latitudinal distribution of major solar flares

Table 1—North-South Asymmetry in Latitude Intervals of 10

Latitude interval deg	$A=\frac{N-S}{N+S}$
0-10	0.291
11-20	0.250
21-30	0.250
31-40	0.245

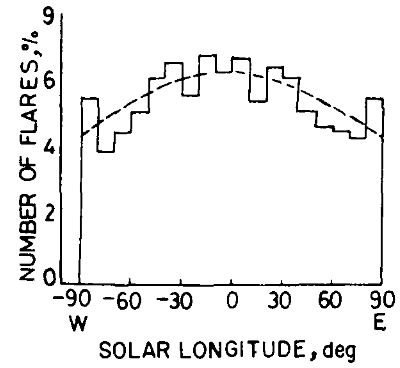

Fig. 2—Solar longitudinal distribution of major solar flares (The dotted line represents the Gaussian curve approximating the data.)

small negative value of $\bar{\phi}$ shows that the frequency distribution is almost similar in both the hemispheres, east and west, and the flares in western hemisphere are slightly higher than those in the eastern hemisphere.

3.2 North-South Asymmetry

The north-south asymmetry $[A=(N-S)/(N+S)]$ of major solar flares from 1955 to 1979 is shown in Table 2. This asymmetry for these major flares from 1955 to 1974 has been studied earlier[7]. It is clear from Table 2 that, generally, the north-south asymmetry is positive, with small and large fluctuations in its values, except during 1958 (in solar cycle 19), 1972 and 1974 (in solar cycle 20) and 1976, 1977 (in solar cycle 21). The negative asymmetry implies that the number of flares are larger in southern hemisphere than the northern hemisphere. Earlier results[7-9] have also reported a negative asymmetry in the case of optical solar flares, PCA-flares and sunspot magnetic classes, in 1958, 1972 and 1974.

The occurrence of major flares in northern and southern hemispheres of the sun is different in the early periods of the cycle 21 as compared to the same periods of the cycles 19 and 20. Also there does not appear to be any strong relationship between N-S asymmetry and 11 or 22 yr cycle of occurrence of major flares though the asymmetry reversed (from positive to negative value) during or around the periods of reversal[14,24] of polarity of solar polar magnetic field (1958 and 1972).

3.3 Long Term Variation

The distribution of major flares in latitudes shown in Fig. 3 is interesting in comparison with Maunder's butterfly diagram. Examining the latitudinal distribution of sunspots from 1874-1913, Maunder[2] showed that the first spots of a cycle occur at approximately 30 N and 30 S. At sunspot maximum, the zone reaches ±15 deg. latitude, and last spot of a cycle appears at approximately ±8. The pattern obtained in Fig. 3 seems to show the details of the Maunder diagram. This result together with the one shown in Fig. 4 suggests that the 19th solar cycle consisted of two pronounced peaks of major flare activity, one in 1957 and the other in 1959-60. The 20th solar cycle consisted of two outstanding peaks in 1967 and 1970. The latest solar cycle (up to 1979) has shown one peak of major flare activity in 1978-79. Also there are two abrupt decreases in the northern hemisphere, the first being in 1958 and the second in 1971. Here it may be worth mentioning that the polarity of the general magnetic field of the sun in the northern hemisphere has changed in 1958 and 1971. The rapid decreases in 1971 in the number of the sunspots, the intensity of the radio emission at 2800 MHz, calcium plages[25] and 530.3 nm

Table 2 North-South Asymmetry of Major Flares in Solar Cycles 19, 20 and 21

Year $A = \frac{N-S}{N+S}$

Year	A	Year	A
Solar cycle 19		**Solar cycle 20**	
1955	0.143	1968	0.164
1956	0.115	1969	0.638
1957	0.274	1970	0.587
1958	−0.257	1971	0.097
1959	0.778	1972	−0.132
1960	0.516	1973	0.024
1961	0.367	1974	−0.316
1962	0.391	1975	0.437
1963	0.636		
1964	1.000	**Solar cycle 21**	
Solar cycle 20		1976	−0.500
1965	0.333	1977	−0.250
1966	0.909	1978	0.138
1967	0.579	1979	0.089

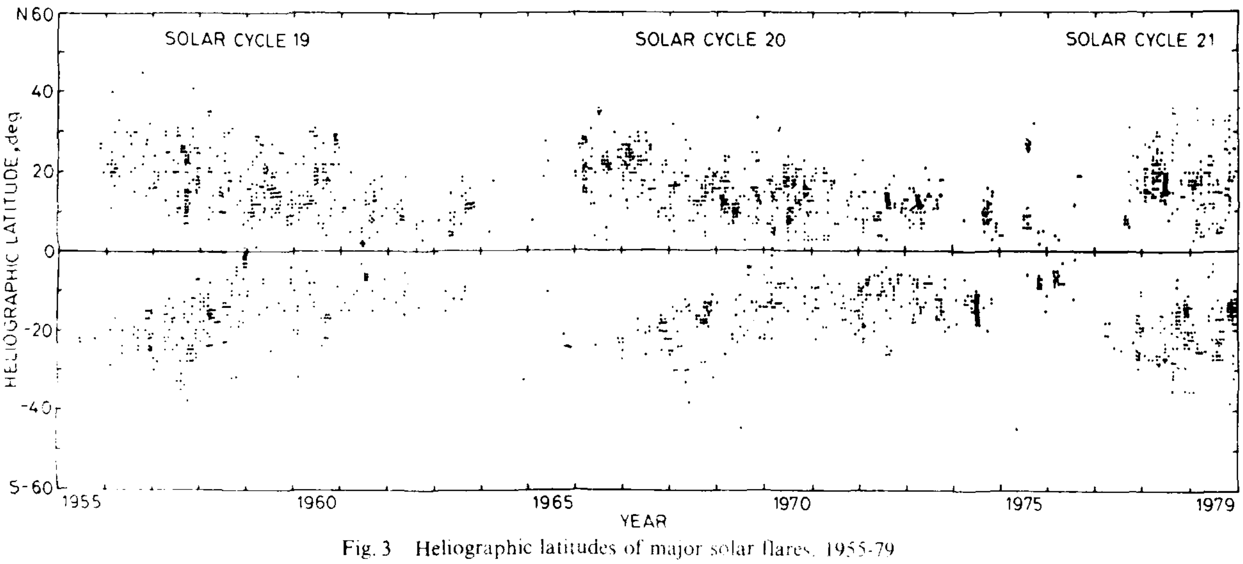

Fig. 3 Heliographic latitudes of major solar flares, 1955-79

coronal emission line[6] have also been reported. Another observation is that the major flare frequency has increased very drastically after 1977, in both the hemispheres, northern and southern. This major flare activity in 1978-79 is the highest of all the years since 1955.

3.4 Sunspot Number-Major Flare Activity Relationship

From the limited data of major flares for less than three solar cycles, it is not possible to reach at any general conclusion regarding the occurrence of major flares with respect to phase of the solar cycle. However, for solar cycles 19 and 20, the relation of major flare occurrence to the sunspot numbers has been studied by us. As shown in Fig. 5, there is a linear relationship between the number of observed major flare events and the sunspot number, although there is a great deal of scattering. Using the flare data of H$_\alpha$ importance $\geqslant 2$ for solar cycle 19 it is shown[17] that the number of flares is nearly proportional to the sunspot number for the case in which these numbers are larger than 100 and that this proportionality breaks down for the cases in which the number of sunspots are less than 100 although the number of observed flares tends to increase as the sunspot number increases. The linear relationship between the transient geomagnetic activity, generated by solar flares or coronal transients, and sunspot number has been reported recently[26].

We also noted, as shown in Fig. 5, that the slopes of the linear curves for the two cycles 19 and 20 are not same, which probably shows that the major flare-sunspot ratio is variable from one cycle to the other.

3.5 Comprehensive Flare Index of Major Flares and Occurrence Frequency

After dividing the events listed[21-23] into six classes according to increasing CFI the relationship of flare occurrence frequency and CFI has been studied for solar cycles 19 and 20 separately and for total period 1955-79 whose data for major flares are available. This relationship is shown in Fig. 6. Fig. 6 shows that flare occurrence frequency first increases for lower values of CFI and then after a certain value it decreases almost exponentially to very small value for the highest CFI An exponential decrease with flare importance has also been found[17] by considering only the flares of high optical importance $\geqslant 2$.

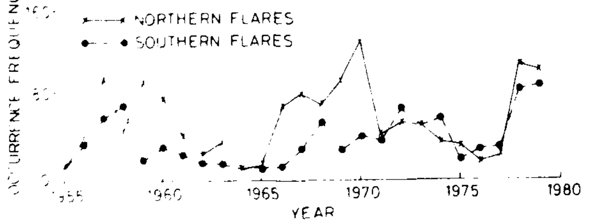

Fig. 4 Annual occurrence frequencies (in numbers) of northern and southern major flares, 1955-79

3.6 Solar Rotation and Solar Activity

Solar activity is basically caused by the interaction between solar magnetic fields, solar rotation and convective motions[27]. The solar cycle related variation of photospheric rotation rate occurs at high latitude. Another cycle related variation observed at latitude greater than 65° is the polar field strength[28]. It was suggested, on the basis of the solar polar rotation rate[29] and the polar magnetic field strength at two preceding minima[30], that the maximum of the cycle 21 may be expected to be very high.

The highest observed monthly mean sunspot number in cycle 19 was 253.8 in October 1957, in cycle 20 it was 135.8 in March 1969 (Ref. 31) and the highest monthly mean sunspot number in cycle 21 was 188.4 in

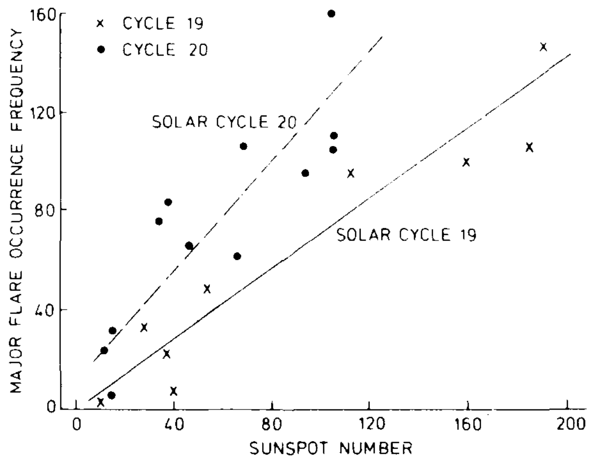

Fig. 5 Relationship of the sunspot numbers to the occurrence of major solar flares (in numbers) for solar cycles 19 and 20

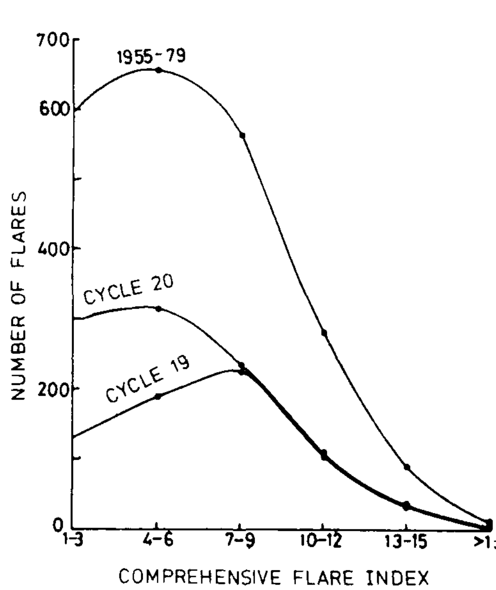

Fig. 6 Relationship of the occurrence of major solar flares to their comprehensive flare index

September 1979 (Ref. 20). The amplitude of major solar flare activity is also high, as shown in Fig. 4, and it is highest for the solar cycle 21. These results are in agreement with the forecast made[29,30] on the basis of solar polar rotation rate and the strength of the polar magnetic fields of preceeding cycles.

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